ESTCP
Cost and Performance Report

(ER-200933)

Renewable Energy Production from DoD Installation Solid Wastes by Anaerobic Digestion

June 2016

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE (08-06-2016)	**2. REPORT TYPE** Cost and Performance Report	**3. DATES COVERED** *(2009 – 2016)*

4. TITLE AND SUBTITLE Renewable Energy Production from DoD Installation Solid Wastes by Anaerobic Digestion	**5a. CONTRACT NUMBER** W912HQ-10-C-0001
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Patrick. J. Evans, Scott Vandenburgh, Tyler Miller, Janelle Amador, H. David Stensel, Donnie Stallman, Urv Patel, Matthew Higgins, Ambalavanan Jayaraman, Gokhan Alptekin, Steve Dietz, Matthew Cates, and Kerry Libberton	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) CDM Smith, 14432 SE Eastgate Way, Suite 100, Bellevue, Washington 98007	**8. PERFORMING ORGANIZATION REPORT NUMBER** 50957.73968.6407.001
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) ER-200933

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Food waste generation and disposal is a significant source of greenhouse gas emissions and lost opportunity for energy recovery. Anaerobic digestion of food waste and purification of methane-rich biogas was conducted at the US Air Force Academy. Cost and performance of the technology with respect to renewable energy efficiency; biogas purification; digester capacity and stability; waste sludge generation and characteristics; operational reliability, safety, and ease of use; and greenhouse accounting were evaluated. Demonstration results indicated the process was capable of meeting or exceeding most performance objectives. The technology was capable of significant reductions in the solid waste stream while at the same time recovering energy that can be used as vehicle fuel or a variety of other uses. Cost-effectiveness of the technology was comparable or better to landfilling and composting especially for larger installations. The technology was also demonstrated to have favorable greenhouse gas offsets compared to composting and landfilling. An engineering guidance document was prepared that provides installations practical approaches for technology evaluation and implementation.

15. SUBJECT TERMS
Food waste, FOG, solid waste, anaerobic digestion, methane, biogas, biomethane, biogas purification, vehicle fuel, renewable energy, net zero, greenhouse gas, food-to-fuel.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	71	**19b. TELEPHONE NUMBER** *(include area code)*

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ACRONYMS AND ABBREVIATIONS

ACSIM	Office of the Assistant Chief of Staff for Installation Management
ADM1	Anaerobic Digestion Model 1
atm	standard atmosphere
BMP	biochemical methane potential
BTU	British Thermal Unit
$CaCO_3$	calcium carbonate
CH_4	methane
CHP	combined heat and power
Co	cobalt
CO_2	carbon dioxide
COD	chemical oxygen demand
d	day
DoD	U.S. Department of Defense
ESTCP	Environmental Security Technology Certification Program
EPACT	Energy Policy Act of 2005
EO	Executive Order
FOG	fats, oils, and grease
ft^3	cubic foot/feet
FY	fiscal year
g	gram(s)
gal	gallon(s)
GGE	gasoline gallon equivalent
GHG	greenhouse gas
GJ	gigajoule(s)
H_2S	hydrogen sulfide
hr	hour(s)
kg	kilogram(s)
kW	kilowatt(s)
kWh	kilowatt hour(s)
L	liter(s)
L/L/d	liters of methane per reactor volume per day
lb	pound(s)
m^3	cubic meter(s)
mg	milligram(s)

min	minute(s)
mL	milliliter(s)
Mo	molybdenum
N^2	nitrogen gas
NDAA	National Defense Authorization Act
NEC	National Electrical Code
NFPA	National Fire Protection Association
Ni	nickel
N/L	nitrogen per liter
O&M	operations and maintenance
O_2	oxygen gas
ppm	part(s) per million
ppmv	parts per million by volume
RCRA	Resource Conservation and Recovery Act
Se	selenium
SELR	specific energy loading rate
SRT	solids retention time
TALK	total alkalinity
TS	total solid
TSD	total solids destruction
TSS	total suspended solid
USAFA	U.S. Air Force Academy
USEPA	U.S. Environmental Protection Agency
VFA	volatile fatty acid
VS	volatile solid
VSA	vacuum swing adsorption
VSD	volatile solid destruction
VSS	volatile suspended solids
VSSD	volatile suspended solids destruction
WERF	Water Environment Research Foundation
WWTP	wastewater treatment plant
yr	year(s)

ACKNOWLEDGEMENTS

This research was conducted with support from the U.S. Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) as Project ER-200933 under Contract W912HQ-10-C-0001 from the U.S. Army Corps of Engineers Humphreys Engineer Center Support Activity. Additional funding was received from the Water Environment Research Foundation (WERF) under project number ENER14R14, and is gratefully acknowledged. In particular, authors would like to thank Dr. Andrea Leeson of ESTCP and Ms. Lauren Fillmore of WERF for their support.

We also wish to acknowledge the support of the U.S. Air Force Academy (USAFA) and the 10th Civil Engineer Squadron including Ms. Amber Baillie, Ms. Ann Brown, Mr. Jay Burgoon, Mr. Keith Butala, Capt. Charles Comfort, Mr. Jack Damien, Ms. Jennie Duncan, Mr. Dan Follett, Ms. Jenny Hewett, Mr. Russell Hume, Mr. Tom Hykes, Mr. Larry Lawrence, Mr. Matt Lewis, Col. Rick LoCastro, Mr. Glenn Loyche, Mr. Philip Marne, Ms. Jennifer McCorkle, Col. Brent Richert, Lt. Col. Mark Russo, Mr. Mark Schmidt, Mr. Chris Simpson, Ms. Tina Springer, Mr. Dan Stewart, Professor Don Veverka, Ms. Corine Weiss, Mr. Gerald Williams, and Capt. Frank Zou. A special thank you goes to Mr. Tom Hykes and Mr. Gerald Williams who were instrumental in the success of this demonstration. We apologize if we have unintentionally missed others at USAFA.

Research into food waste generation by the DoD would not have been possible without the contributions of Ms. Nancy Carper (U.S. Air Force, Air Force Materiel Command, Air Force Civil Engineer Center Environmental Quality Technical Support Branch [AFCEC/CZTQ]), Mr. Bill Eng (Office of the Assistant Chief of Staff for Installation Management [ACSIM]), Ms. Jill Hamilton (Naval Facilities Engineering Command Engineering and Expeditionary Warfare Center [NAVFAC EXWC]), Ms. Cecile Holloway (Headquarters, Department of the Army [HQDA], ACSIM), and Mr. Edmund Miller (Office of the Under Secretary of Defense for Acquisition, Technology and Logistics).

Numerous scientists and engineers from CDM Smith were involved in this demonstration including Ms. Janelle Amador, Mr. Chris Avina, Mr. Cameron Clark, Mr. Cale McPherson, Mr. Tyler Miller, Ms. Diane Nelsen, Ms. Eva Opitz, Dr. Dave Parry, Ms. Jenny Strehler, Mr. Scott Vandenburgh, Mr. Mike Veksler, and the outstanding contributions of numerous people from CDM Constructors. A special thank you goes to Col. Patrice Melancón, formerly with CDM Smith and currently with the U.S. Air Force.

Points of contact for the demonstration are included in Appendix A.

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The U.S. Department of Defense (DoD) is a significant consumer of energy and generator of solid waste. During fiscal year (FY) 2009, the DoD consumed 209 trillion British Thermal Units (BTUs) of energy (2.2×10^{17} J), excluding vehicle fuel. Further, during the same period, the DoD generated 5.2 million tons of solid waste. In 2011, 164 million tons of municipal solid waste was discarded comprised of 21.3% food waste. The energy content is ~130 trillion BTU or ~60% of the FY2009 DoD energy use. Much of this highly biodegradable waste is disposed in landfills where it is anaerobically digested into the greenhouse gases (GHGs) methane (CH_4) and carbon dioxide (CO_2). Anaerobic digestion of food waste in engineered reactors to produce methane-rich biogas offers a sustainable alternative to current practices and a source of energy. Furthermore, this biogas can be purified to produce vehicle fuel and provide GHG offsets.

The performance objectives of this demonstration included various aspects of renewable energy conversion efficiency; digester capacity and stability; biogas purification, solids destruction, and minimization of process residuals; operational reliability; and accounting of GHG emissions. Both quantitative and qualitative performance objectives were evaluated during the demonstration. Energy conversion efficiency of food waste and canola oil (a surrogate for U.S. Air Force Academy [USAFA] grease trap waste) to methane was 73±13% (goal ≥70%). When parasitic energy losses for the process (e.g., heating, pumping, and gas purification) were considered, the efficiency was 62% (goal ≥50%). The volumetric methane production rate was not met (0.82±0.22 liters of methane per reactor volume per day [L/L/d] [goal ≥2]). This was a result of a dilute food waste/canola oil feed, which was rectified later in the demonstration resulting in a rate of 2 L/L/d being observed at the end of the demonstration. Methane recovery during biogas purification by the vacuum swing adsorption (VSA) was 94±2.9% (goal ≥80%). Hydrogen sulfide (H_2S) in the treated biogas was 0.030±0.035 parts per million (ppm) (goal <4). CH_4 in the treated biogas was 98±0.5% (goal ≥95%) after correction for likely air contamination during sampling. Total solids (TS) reduction was 78±3.4% (goal ≥60%). Digestate sulfide was 71 milligrams per liter (mg/L) (goal <500 mg/L). The digestate was a liquid with low total suspended solids (TSS), high ammonia and volatile fatty acid (VFA) concentrations, moderate concentrations of pathogens, and poor dewaterability. Compost amendment is possible though odor could be a concern. The digestate may be useful as a liquid fertilizer considering the concentrations of ammonia and metal nutrients. The process was 93% available during Phase III and 100% available during Phase IV (goal ≥95%). Mechanical malfunctions during Phase III were related to a leaking digester mixer shaft seal. After start-up issues were resolved, the system was easily operated by a single operator working one shift/day (d), five d/week. The calculated GHG emissions from a nominally scaled food waste digester were –470 tons/year (yr) (i.e., GHG offset due to use of purified biomethane as vehicle fuel). By comparison, landfilling and composting would generate 530 and 180 tons/yr, respectively.

TECHNOLOGY DESCRIPTION

Anaerobic digestion plus biogas purification was used to convert food waste to biomethane fuel (food-to-fuel). Anaerobic digestion is a process where a community of anaerobic microorganisms biodegrade organic matter and produce biogas—a mixture of CH_4 and CO_2. Two technologies were demonstrated

for biogas purification biomethane. H_2S and organosulfur compounds were removed using a mixed metal oxide media (SulfaTrap™). A triple-bed VSA unit was used for CO_2 and moisture removal.

The demonstration was conducted at the USAFA in Colorado Springs, Colorado. Four phases were conducted including (I) equipment shakedown, (II) startup, (III) stable operation with diluted digester feed, and (IV) modified process with concentrated digester feed. Biogas purification testing was conducted during Phase IV.

DEMONSTRATION RESULTS

Anaerobic digestion of food waste and a surrogate for grease trap waste (i.e., canola oil) was demonstrated to be capable of recovering potential energy content, reducing solid waste, and potentially producing a valuable, nutrient-rich end product. Biogas purification was demonstrated to be capable of high methane recovery and production of biomethane that was sufficiently pure to be compressed and used as vehicle fuel. When the processes are considered together, they provide a solid waste reduction technology that recovers energy, creates a GHG offset, and produces an end product. The process provides distinct advantages over landfilling and composting with respect to energy recovery and GHG offsets.

The capital and operations and maintenance (O&M) costs of a green field food waste digester and gas purification system was determined for three installation sizes (10,000, 20,000, and 40,000 personnel). Capital costs ranged from $0.93 (10,000 personnel) to $2.44 million (40,000 personnel). Net annual revenues (i.e., income from vehicle fuel minus O&M costs) ranged from –$20,000 (10,000 personnel) to $120,000 (40,000 personnel). When capital costs, O&M, and revenues were considered, the net present cost ranged from $1.28 million (10,000 personnel) to $280,000 (40,000 personnel). The costs for food waste digestion and vehicle fueling were as low as $4/wet ton (40,000 personnel) to $50/wet ton (10,000 personnel). Compare these costs to average landfilling costs of $50/wet ton and composting costs ranging from $29 to $52/wet ton. This economic advantage combined with the minimized GHG emissions and dependence of petroleum-based fuels suggests that food waste digestion and biogas purification is advantageous.

IMPLEMENTATION ISSUES

The project showed that anaerobic digestion of food waste at military bases is technologically feasible and can be cost competitive with alternative methods of food waste management depending on the size of the installation. Often anaerobic digestion systems are custom designed and built. However, in recent years, a number of companies have emerged that specialize in manufacture of onsite anaerobic digestion systems. One important consideration for a military installation is whether the staff is available to operate and maintain what is essentially a wastewater treatment plant (WWTP). Clearly, if the installation already had a WWTP onsite such as USAFA, then the implementation is much easier. Alternatives do exist as described in the Engineering Guidance Document (Vandenburgh and Evans 2016). This document is intended to facilitate technology evaluation, selection, and implementation. The alternatives include transport to a local wastewater reclamation facility that has the capability of accepting food waste and fats, oils, and grease (FOG).

1.0 INTRODUCTION

This report presents a Cost and Performance summary of food waste anaerobic digestion and biogas purification technologies for solid waste reduction and renewable energy generation. Complete demonstration details can be found in the Final Report (Evans et al. 2016). A companion Engineering Guidance Report is also available (Vandenburgh and Evans 2016).

1.1 BACKGROUND

The U.S. Department of Defense (DoD) is a significant consumer of energy and generator of solid waste. During fiscal year (FY) 2009 the DoD consumed 209 trillion British Thermal Units (BTUs) of energy (2.2×10^{17} J), excluding vehicle fuel (DoD 2010). Further, during the same period, the DoD generated 5.2 million tons of solid waste. The consumption of energy and the generation of waste places economic, environmental, and social burdens on the DoD. Food waste is generated worldwide at a rate of ~0.3 kilograms (kg) person^{-1} d^{-1} (USEPA 2008). The DoD is a major producer of solid waste of which a significant fraction is food waste. In 2011, 164 million tons of municipal solid waste was discarded comprised of 21.3% food waste (USEPA 2013). It is estimated that energy content of this annual food waste generation amounts to 130 trillion BTU (1.4×10^{17} J), which is ~60% of the FY2009 DoD energy use exclusive of vehicle fuel. Much of this highly biodegradable waste is disposed in landfills where it is anaerobically digested into greenhouse gas (GHG) such as methane (CH_4) and carbon dioxide (CO_2). The methane produced in landfills is significant and only a fraction is recovered. Food waste and related wastes, including spent cooking oil, has a high energy value (Lenahan and Kirwan 2001; Wolk et al. 2007). Anaerobic digestion of food waste in engineered reactors offers a sustainable alternative to current practices and a source of energy.

The purpose of this demonstration was to validate anaerobic digestion of DoD wastes including pre- and post-consumer food waste, waste cooking oil, and grease trap waste as a viable means of disposal and renewable energy generation. The project demonstrated the ability to digest these wastes in a controlled and predictable manner to maximize the generation of biogas, a methane-rich, high-energy byproduct. The project also studied biogas treatment to remove the non-methane portion of the gas including hydrogen sulfide (H_2S) and CO_2, with the goal to produce treated product gas equivalent in quality to natural gas and suitable for numerous end-use applications, and reduce mass of waste disposed by at least 60%. The pilot system was installed at the U.S. Air Force Academy (USAFA) in Colorado Springs, Colorado, and demonstration activities were conducted for one year. A laboratory treatability study was also conducted in advance of the field demonstration. A simple schematic (**Figure 1**) shows in general terms how the subject technology could be implemented.

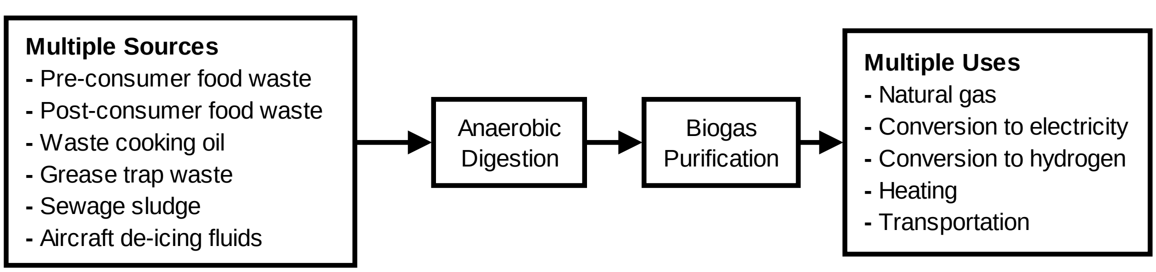

Figure 1. Anaerobic Digestion of Wastes to Produce Fuel.

Combining waste treatment with renewable energy production provides a number of benefits that are not provided by the conventional practices of fossil fuel utilization and landfilling of wastes. The benefits of the subject technology are:

- Production of a high energy product with numerous end uses
  - Provides a significant contribution towards The Energy Policy Act of 2005 (EPACT) and the 2008 National Defense Authorization Act (NDAA) goals of increased renewable energy production and utilization
  - Decreases total energy procurement costs as purified biogas is substituted for natural gas
  - Reduces GHG and pollutant emissions as fossil fuel energy sources are avoided
- Reduced landfilling of a high water waste
  - Reduces waste disposal costs
  - Reduces leachate formation and preserves groundwater quality
  - Extends landfill life and delays construction of new landfills

1.2 OBJECTIVE OF THE DEMONSTRATION

The general objective of the research reported here was to demonstrate stable anaerobic mono-digestion of food waste at the pilot scale. An additional objective was to demonstrate two innovative technologies for biogas purification to natural gas-quality methane. The quantitative performance objectives of this demonstration/validation project are:

- Renewable energy conversion with respect to overall energy conversion, methane production, and biogas composition
- Gas purification with respect to meeting natural gas specifications
- Digester capacity/stability with respect to volumetric volatile solids (VS) and chemical oxygen demand (COD) loading rates, specific energy loading rates (SELRs), pH, and the ratio of volatile fatty acids (VFAs) to total alkalinity (TALK)
- Waste sludge with respect to total solids (TS) reduction, total sulfide, and leachable metals
- Class 503(b) biosolids requirements with respect to solids retention time (SRT) and VS destruction
- Operational reliability

The performance objectives were met with a few exceptions. A complete listing of quantitative and qualitative performance objectives and how each was met is included in Section 3.

1.3 REGULATORY DRIVERS

Regulatory drivers for this technology include the following:

- EPACT mandates that Federal facilities receive at least 7.5% of their electricity from renewable resources by 2013. If the energy is generated onsite from renewable resources, the facilities receive double credit toward attainment of this goal.
- The NDAA implemented a renewable energy goal of 25% for the DoD.
- Executive Order (EO) 13423 requires that at least half of the statutorily required renewable energy consumed by the agency in a fiscal year comes from a new renewable source and to the extent feasible, the agency implement renewable energy generation projects on agency property for agency use. Further, the order requires increased diversion of solid waste as appropriate and maintenance of cost-effective waste prevention and recycling programs in its facilities (USDOE 2008).
- The DoD Integrated (Non-Hazardous) Solid Waste Management Policy set minimum standards of 40% waste diversion of non-hazardous, non-construction, and demolition-integrated solid waste (Beehler 2008).
- The DoD Strategic Sustainability Performance Plan provides an approach towards meeting these requirements, and includes a focus on: (1) reducing energy needs and reliance on fossil fuels, and (2) water resources management.
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 189.1-2009, Leadership in Energy and Environmental Design (LEED), and various Energy Policy Acts all have required more sustainable use of energy.
- The Army has implemented a Net-Zero installations policy seeking to increase and improve sustainability on installations.

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2.0 TECHNOLOGY

This section provides an overview of the anaerobic digestion and biogas purification technologies.

2.1 TECHNOLOGY DESCRIPTION

Anaerobic digestion is a process where a community of anaerobic microorganisms biodegrade organic matter and produce a mixture of CH_4, CO_2, and other gases such as H_2S, albeit in smaller concentrations. While the biochemical reactions are complex, the general mechanisms involve solids biohydrolysis followed by fermentation of complex organics to hydrogen and VFAs including acetic, propionic, and butyric acids. These simpler compounds are subsequently converted to methane by methanogenic microorganisms. A schematic representation of the anaerobic digestion process is presented in **Figure 2.**

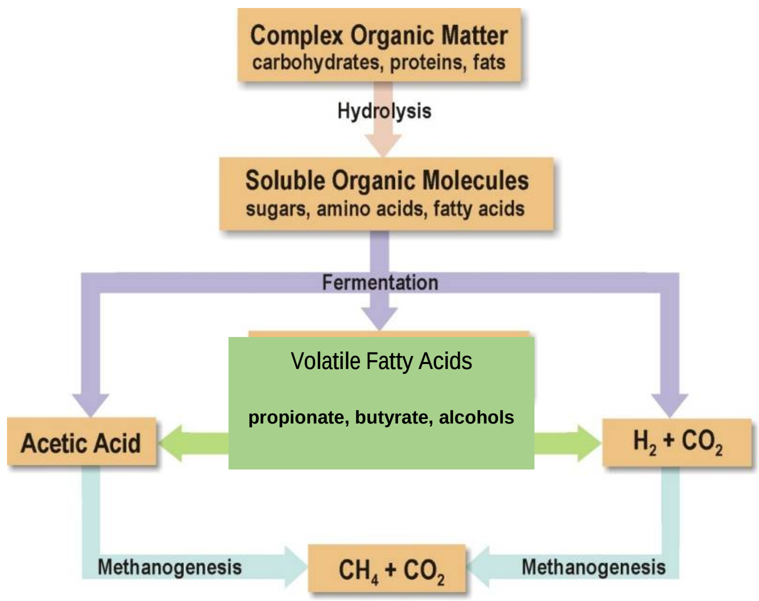

Figure 2. Simplified Anaerobic Digestion Schematic (USEPA 2011).

Figure 3 is a simplified process flow diagram for the demonstration system installed and operated at the USAFA waste water treatment plant (WWTP). Two replicate digesters were continuously mixed and temperature controlled (37 ^oC). Biogas from the digesters was combined and routed through SulfaTrap™-R7 mixed metal oxide adsorbent (TDA Research, Wheat Ridge, Colorado) for H_2S removal. The biogas then flowed to a biogas holder. Biogas was then discharged to the USAFA flare. The process was modified between Phases III and IV as illustrated in **Figure 3.** The purpose was to eliminate water addition to the food waste/canola oil mixture. Digestate was recycled and mixed with the food waste/canola oil mixture to make it pumpable. Near the end of the demonstration in Phase IV, biogas stored in the holder was purified using a vacuum swing adsorption (VSA). The VSA is based on a regenerable mesoporous carbon media modified with surface functional groups to reduce the CO_2 and H_2O concentration in the biogas to pipeline specifications. The adsorption of CO_2 from the biogas stream is carried out at the biogas delivery pressure (~1.3 standard atmosphere [atm]), while the sorbent is regenerated and CO_2 recovered under vacuum (at ~0.2 atm). The bed is subsequently pressurized with the feed (biogas) gas.

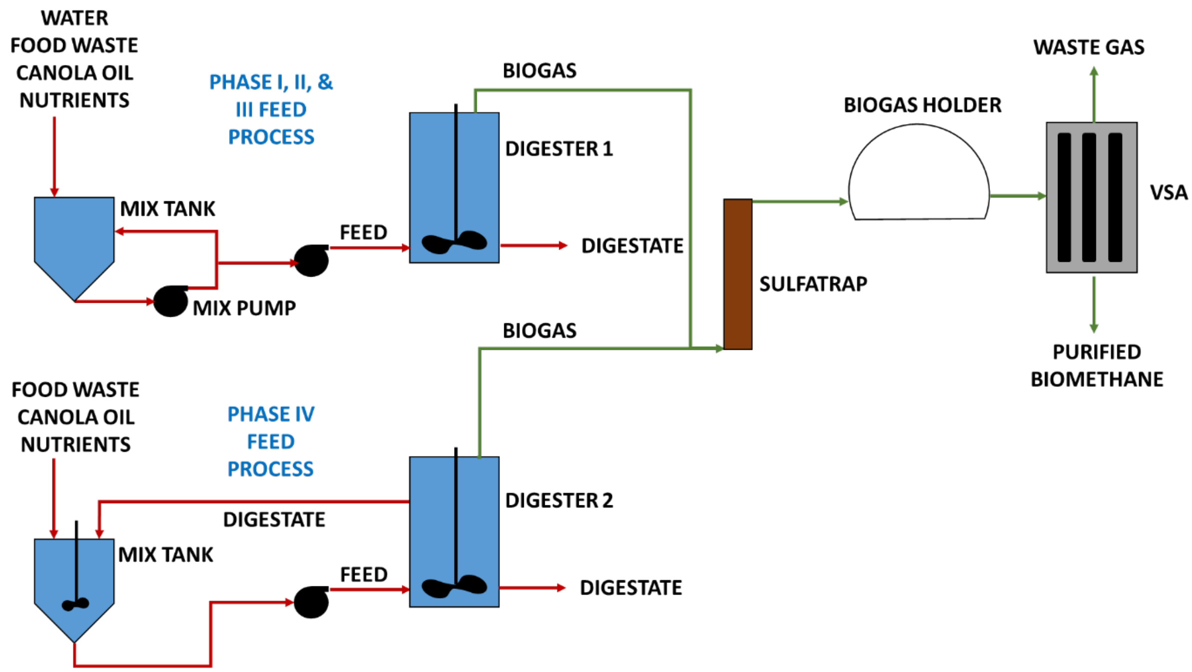

Figure 3. Process Flow Diagram.

A brief timeline of the development of anaerobic digestion is provided below (Burton and Turner 2003; Meynell 1976).

1808	Sir Humphrey Davy determines that methane gas can be generated from cow manure
1859	First anaerobic digester is built in a leper colony in India
1895	Anaerobic digesters used in Exeter, England, to fuel street lamps
1912	Birmingham, England, and Baltimore, Maryland, use first large-scale commercial digesters for sewage sludge
1926	First modern digester in Antigo, Wisconsin (covered, heated, mixed, continuously fed, methane collected)
1950s	Most large central sewage treatment plants incorporate anaerobic digestion into their treatment process
1970s	Clean Water Act spurs WWTP construction across the United States and widespread implementation of anaerobic digestion
1970s	Oil crisis increases interest in anaerobic digestion for energy generation. Large-scale farm digesters constructed in Europe
1990s	Over 200 organic waste digestion systems are installed in Europe, predominantly in Scandinavian countries

1993 Regulations are instituted regulating digestion processes and disposal of biosolids from WWTP (USEPA 1993)

2002 City of Toronto begins testing anaerobic digestion of source-separated food waste

2003 East Bay Municipal Utility District (EBMUD) begins co-digestion of sewage sludge with food and slaughter house wastes

2006 U.S. Environmental Protection Agency (USEPA) studies controlled co-digestion systems for increased stability and throughput

2008 Water Environment Research Foundation (WERF) initiates study on co-digestion of food waste with wastewater solids

A brief timeline showing the development of gas treatment follows.

1895 Anaerobic digesters used in Exeter, England, to fuel street lamps—no gas treatment used

1950s Biogas used for digester and space heating, moisture, and H_2S removal

1970s Advanced gas treatment technologies are developed (membranes, specialized media, scrubbers) but rarely implemented

1980s Biogas utilization for heat and power generation becomes commonplace at large-scale WWTP. Gas treatment for H_2S, moisture, and particulates dominates

1986 First large-scale WWTP in the United States upgrades biogas to natural gas quality with water tower scrubber

1990s Gas quality requirements for boilers and engines become more stringent

1990 SulfaTreat developed for H_2S removal

1996 Specialized media and packaged filter systems for siloxane treatment are commercialized

1997 Pressure swing adsorption (PSA) units are commercialized for CO_2 removal

2000s Advanced gas treatment technologies are commonplace for all major biogas utilization projects

2001 Molecular sieve commercialized for CO_2 removal

2002 Chemical adsorption for removal of CO_2 from biogas commercialized in Europe by Purac

2003 Water tower scrubber for removal of CO_2 from biogas commercialized in Europe by Ros Roca

2.1.1 Application of Technology

While these technologies are being used increasingly around the world, there is no known installation that combines these technologies to generate a natural gas quality product solely from food waste. The project will build off of previous research to demonstrate, validate, and promote the technology to encourage its transfer and implementation across the DoD and the United States. Possible applications for the food waste digestion technology include:

- Implementation at permanent installations to reduce food waste disposal costs and generate renewable energy
- Use on forward operating bases to reduce waste disposal demands while providing a grid-independent and mobile energy supply
- Implementation at any site with a food waste disposal burden including universities, towns, cities, grocery stores, farms, schools
- Enhancement of waste-activated sludge digestion (i.e., co-digestion)

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages and limitations of the subject technology have been summarized in **Table 1**.

Table 1. Advantages and Limitations of the Food Waste Digestion Technology.

Advantages
Combines waste handling and renewable energy generation
Reduces waste disposal of organics by at least 60%
Is scalable and can be combined with other waste handling practices like composting, gasification, and pyrolysis
Generates a renewable energy product with numerous proven end uses
Relies on technologies that have been used and proven for >100 yr
Operation is simple and effective
Anaerobic digestion and biogas treatment are proven processes operated at hundreds of full-scale facilities around the world
Limitations
Is capable of treating only biodegradable solid wastes
Requires sorting of organic wastes from mixed waste stream

For comparative purposes, prominent alternative technologies have also been identified. A matrix comparison of these technologies identifying some of their advantages has been provided in **Table 2**. Items with an “X” indicate that technology has generally demonstrated this capability, while blank boxes indicate a deficiency and a potential limitation of the technology.

Table 2. Alternative Food Waste Digestion Technologies.

Criteria	Landfilling	Incineration	Composting	Co-Digestion	Hog and Fish Feed	Pyrolysis	Gasification
Established technology	X	X	X	X	X		
Limited operator input (onsite)	X	X	X	X	X		
Renewable energy generation	X	X		X		X	X
Produces valuable end product			X		X		
Low land requirement		X	X	X	X	X	X
Good public acceptance			X	X	X		
Treat large volumes	X	X	X	X		X	X
Scalable and portable			X	X			

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3.0 PERFORMANCE OBJECTIVES

Quantitative and qualitative performance objectives were developed to evaluate the technology and to guide the development of a testing plan. The objectives provided the basis for evaluating the cost and performance of the technology. The performance objectives along with the corresponding metrics, data requirements, and success criteria are summarized in **Tables 3** and **Table 4**.

Table 3. Quantitative Performance Objectives.

Performance Objective	Data Requirements	Success Criteria	Phase III Result	Phase IV Result	Criterion Met?
Quantitative Performance Objectives					
Renewable Energy Conversion	Energy Conversion	≥70% energy conversion at 24 d-SRT (not accounting for parasitic demands)	73±19	62±40	**Yes** during Phase III. **No** during Phase IV however energy conversion increased over time and operation had not reached steady state. Note SRT was >24 d.
		≥50% energy conversion at 24 d-SRT (including parasitic demands and conversion to CNG)	63	NA	**Yes**
	Methane production	≥310 L CH_4/kg VS loaded (5 cubic feet per pound [ft^3/lb])	360±70	490±140	**Yes**
		≥190 L CH_4/kg COD loaded (3 ft^3/lb)	270±75	230±150	**Yes**
		≥2 L CH_4/L digester/d (2 ft^3/ft^3/d)	0.82±0.22	1.1±0.65	**No** in Phase III. **No** during Phase IV. **Yes** at end of Phase 4 when methane production was 2.0 liters of methane per reactor volume per day (L/L/d).
	Biogas composition	≥60% CH_4 in biogas	59±4.6	61±6.6	**Yes**
Gas Purification	Natural Gas Specifications	≥80% CH_4 recovery	NA	94±2.9	**Yes**
		<4 ppm H_2S	NA	0.030±0.0.5	**Yes**
		≥95% CH_4 in treated biogas	NA	98±0.5	**Yes** after data corrected for air contamination during sampling. Result prior to correction is 94±2.9%.
		<3% N_2 and CO_2 in treated biogas	NA	3.1±2.0 N_2 2.1±0.4 CO_2	**Partly** - atmospheric exposure appears to have occurred during sampling.

Performance Objective	Data Requirements	Success Criteria	Phase III Result	Phase IV Result	Criterion Met?
		<0.2% O_2 in treated biogas	NA	1.2±0.6	**No** - atmospheric exposure appears to have occurred during sampling.
Digester Capacity/ Stability	Volumetric VS loading rate	≥3.2 g VS/L/d (0.2 lb VS/ft^3/d)	2.4±0.6	2.0±1.2	**No** in Phase III. **Possibly** in Phase IV during last 20 d = 2.9±0.8 g/L/d.
	Volumetric COD loading rate	≥4.8 g COD/L/d (0.3 lb COD/ft^3/d)	3.0±1.0	4.4±2.7	**No** in Phase III. **Possibly** during the last 20 d of Phase IV (5.3±1.8 g/L/d).
	SELR	≥0.26 g-COD/g-VSS/d (0.26 lb/lb/d)	0.44±0.17	0.47±0.30	**Yes**
	pH	6.8 to 7.8	7.8±0.1	7.6±0.1	**Yes**
	VFA/TALK	VFA/TALK <0.2 g-acetate equivalents/g-$CaCO_3$	0.15±0.09	0.12±0.09	**Yes**
Waste Sludge	TS Reduction	≥60% TS reduction – at 24 d SRT	78%±3.4%	92%±2.1%	**Yes** although SRT was >24 d. The Phase IV result is likely overestimated because <1 SRT occurred.
	Total sulfide	<500 mg/kg reactive sulfide	NA	71	**Yes** - Result is for the liquid digestate in units of mg/L.
	Leachable metals	Passes TCLP	NA	<TCLP criteria	**Yes**
Class 503(b)	SRT	≥15 d	40±14	130±91	**Yes**
	VS destruction	≥38%	81%±3.0%	93%±1.8%	**Yes** based on both soluble and suspended VS. In Phase III the result based on VSS was 92±2.7%. The Phase IV result is likely overestimated because <1 SRT occurred.
Operational Reliability	Operations hours	≥95% availability of process equipment	93%	100%	**No** during Phase III due to a leaking mixer shaft seal. **Yes** during Phase IV.

$CaCo_3$ – calcium carbonate, g – gram(s), lb – pound(s), mg – milligram(s), N_2 – nitrogen gas, O_2 – oxygen gas, ppm – part(s) per million, TCLP – toxicity characteristic leaching procedure, VSS – volatile suspended solids

Table 4. Qualitative Performance Objectives.

Performance Objective	Data Requirements	Success Criteria	Criteria Met?
Qualitative Performance Objectives			
Safety	OSHA Accident report forms	Zero lost-time accidents	**Yes** - no zero-lost time accidents. However, exposure to H_2S did occur due to a leaking mixing shaft seal.
		Elimination of all relevant ignition and fire hazards	**Yes** - The process equipment was designed in accordance with the National Electrical Code (NEC) for Class 1, Division 2.
Capacity/Stability	Operating data under a variety of conditions	Capable of stable operation under a range of realistic operating scenarios	**Yes** - Food waste composition varied widely and the digesters were stable.
		Identify limits of QAC and fats, oils, and grease (FOG) loading	**No** - Upper limits of FOG were not determined, however the amount of FOG that was used was quantified and resulted in stable operation. QAC sanitizers were no longer used at USAFA and limits could not be quantified.
Residuals Characteristics	Pathogens, HPC, microbial characterization	Suitability for composting	**Yes** - Digestate contained *E. coli* and fecal coliforms. Presence of other pathogens not determined.
	BOD, TSS, ammonia	Determine residual handling requirements	**Yes** - COD and ammonia were high and TSS was low. Residual was a liquid rather than a solid and may be suitable as a fertilizer or compost amendment. BOD was not measured but can be assumed to be half of the COD.
Market Compatibility	Feedback from composters and USAFA base	Acceptable as feedstock for compost	**Possibly** - Digestate was rich in COD and nutrients but the high VFA content could lead to odor complaints.
Ease of Use	Feedback from operators	Safe and reliable operation by a single operator	**Yes** - Provided automated food waste handling and foreign debris segregation is implemented.
	Shutdown report		NA
GHG Accounting	Carbon balance on food waste digestion	Documentation of direct emissions associated with food waste digestion and gas treatment activities	**Yes**

$CaCo_3$ – calcium carbonate; HPC – heterotrophic plate count; OSHA – Occupational Safety and Health Administration; QAC – quaternary amine compound; TSS – total suspended solid; VSS – volatile suspended solids

4.0 SITE DESCRIPTION

The pilot plant was installed at the USAFA WWTP located approximately ten miles north of downtown Colorado Springs off Stadium Boulevard and Community Center Drive. The unit was installed on the north end of the plant's anaerobic digesters as this space was easily accessible for construction, had nearby utilities that were tapped for connections, the existing digesters and biogas flare were available for management of the digested waste and excess biogas, and the site is reasonably close to Mitchell Hall, the source of the food waste feedstock. An aerial photograph showing the proposed site is provided in **Figure 4**. A map showing the location of Mitchell Hall and the WWTP is provided in **Figure 5**.

USAFA had many characteristics that made it an excellent site for the demonstration. These characteristics included the following:

- USAFA educates 4,500 cadets who eat 3 meals/d, 7 d/week at Mitchell Hall. Thus, a readily available source of food waste existed. A review of billing statements and operating procedures revealed generation rates of 5 tons of food waste and 170 pounds (lb) of fats, oils, and grease (FOG)/week.
- Food waste is sluiced off of plates and containers, ground, and dewatered prior to being bagged and dropped into roll-off containers for landfilling. This pretreatment makes transport and handling of the digester feed stock efficient. The ground and dewatered food waste can be collected in 5-gallon (gal) buckets and transported to the digester.
- An operational WWTP is on base and provided an excellent location for the demonstration. An open area north of the existing full-scale digesters (see **Figure 4**) was available for demonstration equipment. This location provided utilities including electricity, natural gas, and non-potable/potable water. Digestate from the pilot digesters was capable of being discharged into USAFA digester 1 (i.e., the primary digester). Demonstration digester off-gas was able to be routed to an existing flare that is currently used to burn full-scale digester biogas. The full-scale digesters were also a source of seed for the demonstration digesters.

Figure 4. Aerial View of Demonstration Site.

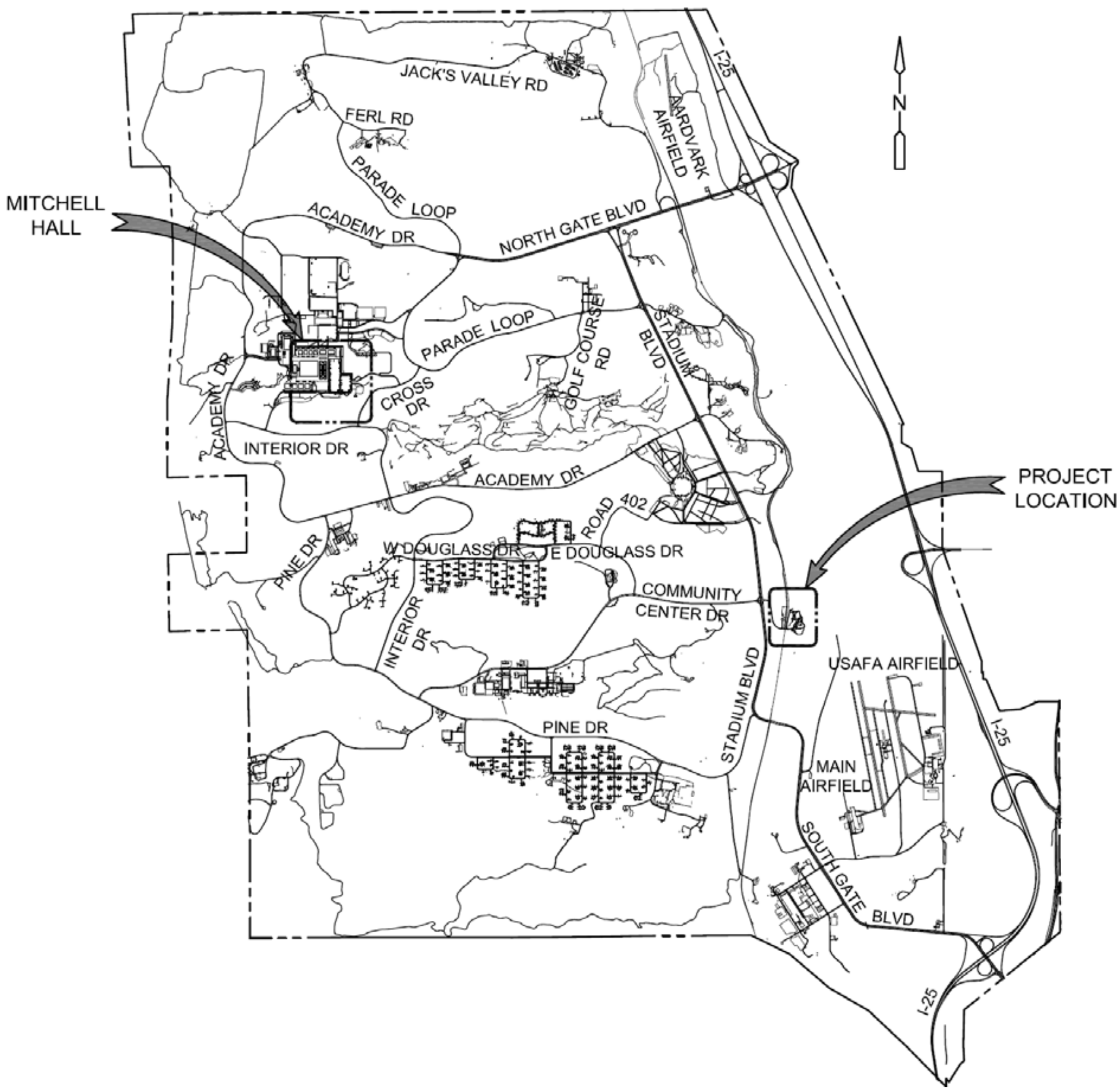

Figure 5. Map of Demonstration Site.

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5.0 TEST DESIGN

This section provides a description of the demonstration design and testing conducted to address the performance objectives described in Section 3.0.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The field demonstration involved anaerobic digestion of a food waste/canola oil mixture to produce biogas and purification of the biogas with a sorbent for sulfur compounds and a VSA system for removal of CO_2 and moisture from the biogas in order to meet natural gas specifications. The demonstration included four phases. Two replicate digesters were operated in Phases I–III and a single digester was operated in Phase IV.

Phase I focused on troubleshooting mechanical problems associated with the equipment plus refining digester feeding, and sampling and analysis protocols to improve operations and increase data reliability. Phase II involved restarting the digesters and establishment of stable operating conditions. Phase III involved a period of stable operation during which food waste/canola oil digestion and biogas production was studied and optimized. At the end of Phase III, performance objectives with respect to organic loading rates and volumetric methane production rates were not met; the feeding strategy was hypothesized to have been the cause. The feeding strategy used in Phases I–III involved mixing food waste and canola oil with tap water to obtain a pumpable slurry that contained ~10% TS or less. Feeding this diluted food waste/canola oil mixture limited the volatile suspended solids (VSS) concentration and associated concentration of microorganisms in the digester, which effectively limited the ability to increase the organic loading rate. The feeding process was modified for Phase IV to allow feeding of a more concentrated food waste/canola oil mixture to the digester. The modification involved elimination of tap water for dilution. Rather, a portion of digestate was mixed with the food waste/canola oil and the resultant mixture was pumped back into the digester. This approach resulted in effectively feeding the digester with an "undiluted" food waste/canola oil mixture that contained >20% solids. Biogas purification testing was conducted during Phase IV.

5.2 TREATABILITY STUDY

A laboratory treatability study was conducted in CDM Smith's Environmental Technologies Laboratory between May 2010 and May 2011. The treatability study focused on: (1) food waste and grease trap waste characterization; (2) quantification of biochemical methane potential (BMP); (3) operation of semi-continuous digesters to determine operating limits, collect performance data, and establish demonstration performance objectives; (4) measurement of hydrolysis kinetics; and (5) adaptation of Anaerobic Digestion Model 1 (ADM1) to a PTC Mathcad platform and simulation of food waste digestion. The results of the treatability study are presented in the Final Report and are summarized below and elsewhere (Amador et al. 2012; Evans et al. 2012; Stallman et al. 2012).

The primary conclusions from the treatability study were as follows:

- The average BMP of the food wastes was 390 milliliters (mL)/gram (g) COD, which suggests that the wastes were highly degradable by anaerobic digestion. The grease trap waste produced the highest methane yield with 700 mL/g COD. This supports the readily-degradable nature of this waste, but also suggests that it enhanced digestion of the sewage sludge inoculum.
- The methane yield was quite variable between the wastes, and a correlation with the fat and protein content of the food waste was found. The fat-plus-protein content appears to be a useful and practical parameter for screening co-digestion wastes.
- Digestion of high-fat wastes can be operationally challenging. Therefore, proper acclimation and adaptation to new high-energy wastes is critical. Mitchell Hall grease trap waste was not uniquely inhibitory since canola oil caused similar inhibition.
- Acclimation of the digesters to high loading rates and grease trap waste was successful using two different strategies. One strategy involved starting with a feed comprised of 90% food waste and 10% grease trap waste (i.e., on an energy basis) and gradually increasing the energy loading rate from 4 to 10 g-COD L^{-1} d^{-1}. Another strategy involved starting with a feed comprised of food waste only at an energy loading rate of 10 g-COD L^{-1} d^{-1} and gradually increasing the grease trap waste energy percentage from 0 to 10%.
- In addition to acclimation, supplementation with trace metal nutrients and feeding concentrated (rather than diluted) food waste was necessary. Trace metals analysis revealed that these food wastes were deficient in cobalt (Co) and nickel (Ni), and possibly molybdenum (Mo). Feeding organic waste at a high VS concentration also proved necessary for stable digester operation. The food wastes were highly degradable, with VS destruction rates >75%. Feeding the waste at VS concentrations typically used anaerobic sludge digestion resulted in digester solids concentrations too low to support stable operation. Digester performance improved when the food waste VS concentrations were kept at >10%.
- The SELR (g-COD g-VS^{-1} d^{-1}) was introduced as a new concept and an alternative to the traditional volumetric solids loading rate (g-VS L^{-1} d^{-1}). The SELR is based on the energy balance and metabolic limits of digester microbial communities. It is especially appropriate for new and diverse organic feed stocks being considered for anaerobic digestion. Support for the SELR concept included observed relationships between digester stability and SELR values. While refinement is required, a maximum SELR 0.4 g-COD g-VS^{-1} d^{-1} appears to be justified for stable digester operation for food waste.

5.3 FIELD TESTING

Food waste was collected from USAFA Mitchell Hall on an as-needed basis generally around lunch time and sometimes around breakfast time. The food waste was ground at USAFA using a commercial pulper system prior to landfilling (**Figure 6**).

Figure 6. Food Waste at Mitchell Hall Was Manually Scraped into Recirculating Sluice Water, Which Was Then Ground in a Pulper/Shredder.

(a) The slurry gravity-drained down one floor into dewatering equipment. (b) Dewatered and ground food waste (c) dropped into a roll off container (d) on the floor below where it was sent to a landfill. Food waste was collected in 5-gal buckets from the dewatering system (c).

The digesters (**Figures 7** and **8**) were seeded with mesophilic anaerobic digester sludge from the USAFA WWTP primary digester. Seeding for Phases I, II, and IV occurred on July 24, 2013, December 20, 2013, and June 6, 2014, respectively. Phase III was a continuation of Phase II and did not involve digester seeding. Food waste was mixed with canola oil and nutrients prior to being fed to the digester. Canola oil was used as a surrogate for USAFA grease trap waste based on treatability study results. Canola oil was added so that it comprised ~10% of the food waste/canola oil VS. Nutrients dosing was based on treatability study results.

Figure 7. Biogas Holder Adjacent to the Demonstration Trailer.

Figure 8. Insulated Digester Tank and Foam Pot.

Operation during Phase I had numerous challenges as the system was started up. These challenges included mechanical failures, issues with inert debris in the food waste plugging and jamming piping and equipment, leaks in the gas handling system, limited availability of food waste, and loss of heating. These issues were resolved and the digesters were restarted in Phase II. Digester feeding generally occurred on Monday, Wednesday, and Friday. The feeding process during Phases II and III involved addition of water to the mix tank followed by addition of food waste, canola oil, and a nutrient stock solution to achieve a TS concentration ~10%. The food waste was screened manually to remove non-food debris. The mixture was recirculated for ~10 minutes (min) prior to being fed to the digester. The digesters were drained prior to feeding by a volume equal to the planned feed mixture volume. This approach prevented draining of newly added feed and maintained a constant digester liquid volume. During Phase IV only one digester was operated because one of the digesters incurred a failure of its mixing shaft seal. Food waste and canola oil were mixed with recycled digestate instead of city water. Sufficient digestate was used to reduce the food waste/canola oil mixture TS to ~10% and then pumped back into the digester. Testing of the TDA SulfaTrap™ (**Figure 9**) and VSA (**Figure 10**) systems was conducted during Phase IV. Biogas produced by the digester was treated for sulfur removal in a column containing SulfaTrap™ and then stored in a biogas holder. The three-bed VSA system (**Figure 10**) was designed for 24/7 continuous operation and can treat up to 85 L/min (3 cubic feet [ft^3]/min).

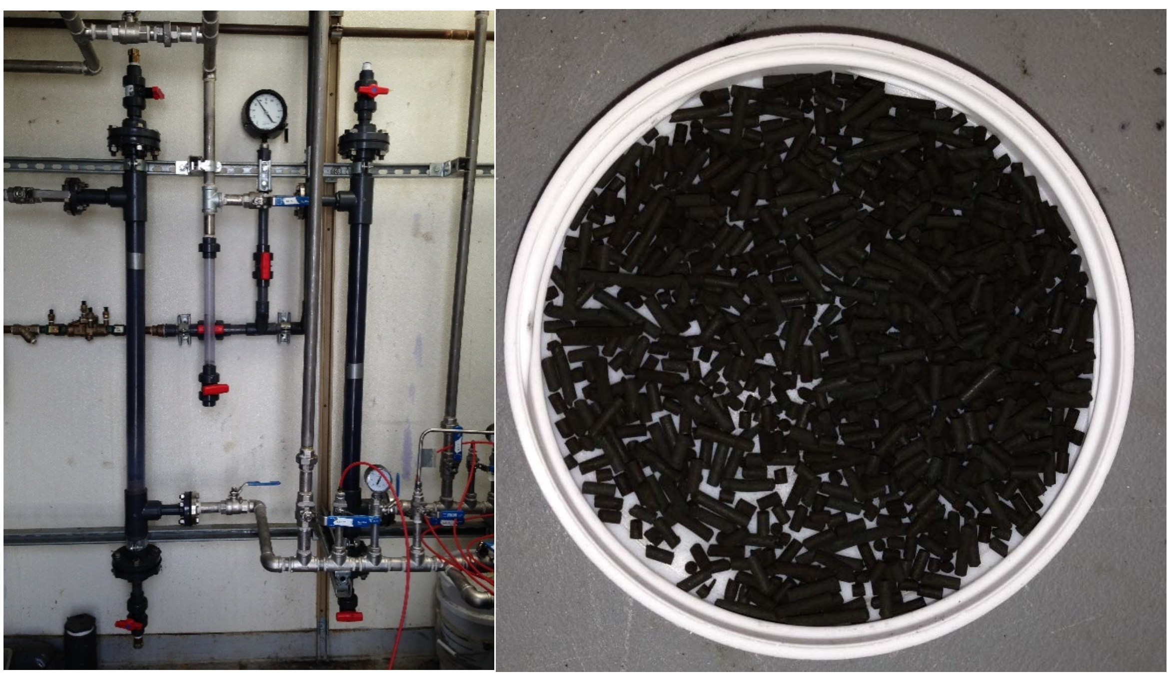

Figure 9. Gravel and SulfaTrap™ Columns in Series, and Photograph of SulfaTrap™ Media.

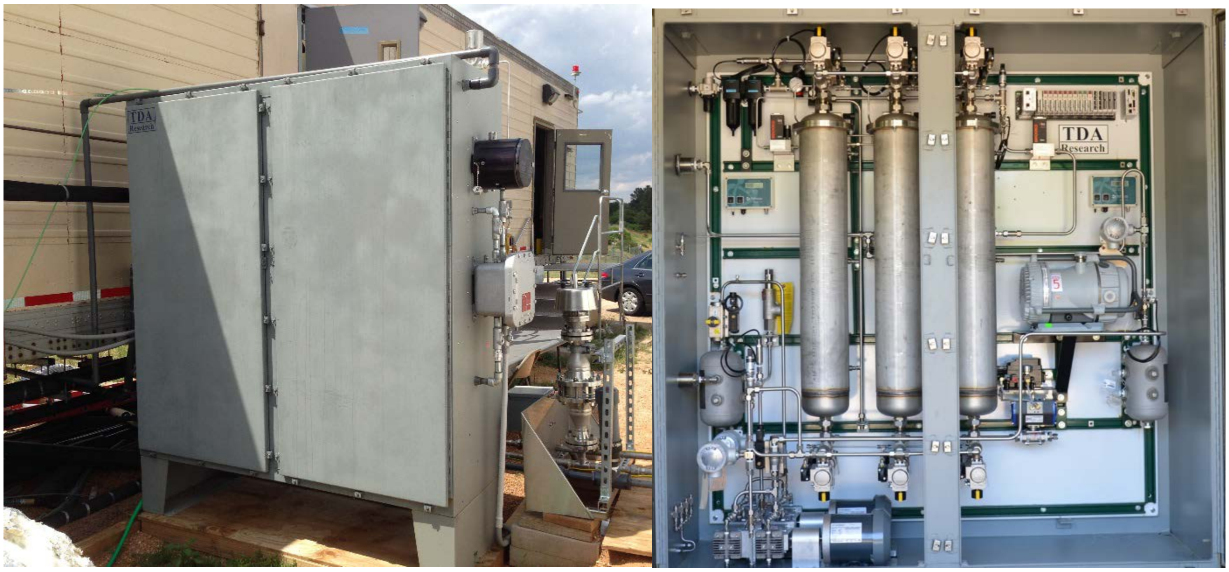

Figure 10. VSA System.

The four phases of operation are shown graphically in **Figure 11**, which shows the trending of the pH and biogas methane content during the operational phases. **Table 5** shows the relationship between dates of operation and elapsed time for the four phases.

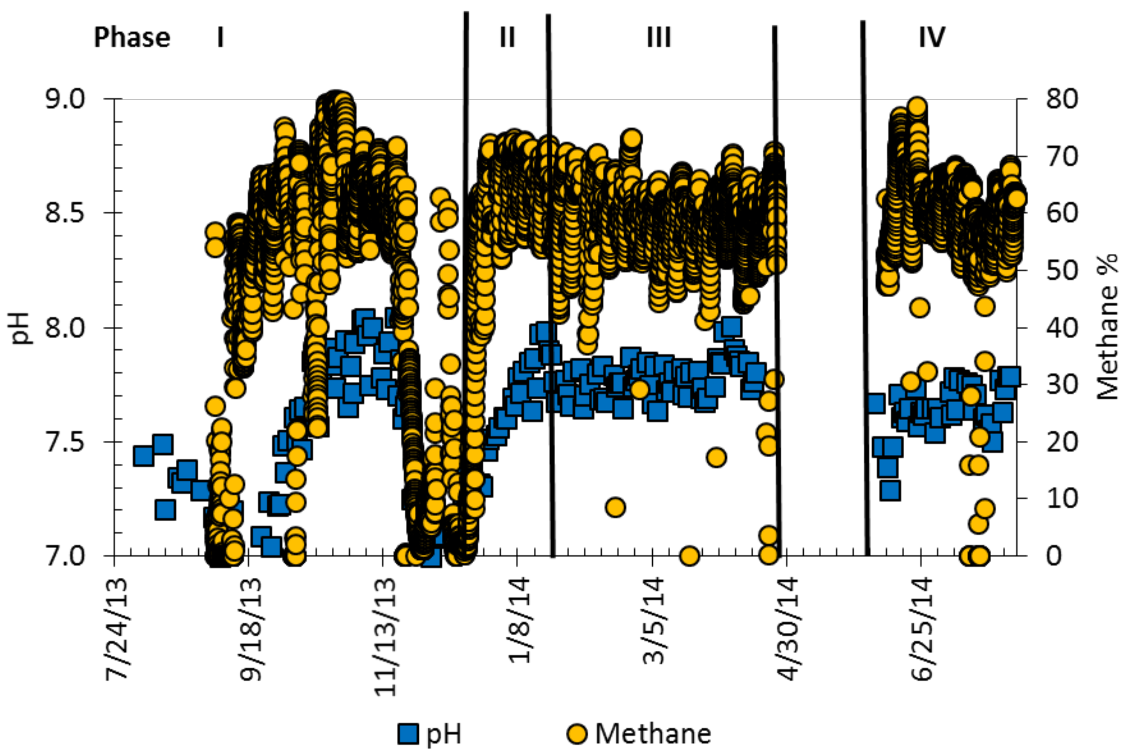

Figure 11. pH and Biogas Methane Concentration Trends During the Four Demonstration Phases.

Table 5. Demonstration Phases.

Phase	Dates	Elapsed Time (d)
I. Shakedown	7/24/13 to 12/19/13	0 to 148
II. Restart	12/20/13 to 1/21/14	0 to 32
III. Stable Operation	1/22/14 to 4/25/14	33 to 126
IV. Modified Feeding Strategy	6/6/14 to 8/4/14	0 to 59

5.4 SAMPLING METHODS

System monitoring and sampling involved a combination of online instruments and grab samples. In general, grab sampling was conducted weekly. Grab samples of food waste were collected from a single bucket. Digester feed samples during Phases II and III were collected from the mix tank after addition of food waste, canola oil, nutrients, and water. During Phase IV, samples of food waste/canola oil mixed with digestate were not collected because of hazards associated with H_2S exposure. Rather, undiluted food waste sampling and analysis was used to determine digester loading. Digestate sampling was conducted by opening a valve at the bottom of the digester. Gas sampling for analyses of fixed gases (CH_4, CO_2, nitrogen gas [N_2], and oxygen gas [O_2]) and sulfur compounds was conducted using Tedlar® bags connected to sample taps on the biogas lines. Sampling for analysis of fixed gases from the VSA was conducted using Tedlar® bags.

Analyses were conducted by certified laboratories (ALS Environmental in Kelso, Washington and Simi Valley, California) using standard methods with the following exceptions. VFAs were analyzed using high-performance liquid chromatography. COD analysis of food waste and digester feed was conducted according to the Standard Operating Procedure (SOP) included in the Final Report. In summary, food waste samples were weighed, mixed with a known volume of water, and blended in a Vitamix® blender until homogenized. Serial dilutions were then conducted until the COD was in the range of the Hach COD test (50–1,500 milligrams per liter [mg/L]). The standard procedure for the Hach analysis was then followed. COD of the food waste was calculated by multiplying the Hach COD reading by the dilution factor. Sulfur in the spent SulfaTrap™ media was analyzed by Hazen Research (Golden, Colorado) using a LECO model S-200 Sulfur Determinator. Details on analytical methods are included in the Final Report.

5.5 SAMPLING RESULTS

5.5.1 Food Waste and Feed Characteristics

The characteristics of the undiluted food waste, the food waste/canola oil mixture, and the digester feed are shown in **Table 6**. These characteristics are for food waste samples following manual removal of non-food debris that included foil and plastic wrapping, plastic utensils, Styrofoam™, bottle caps, and Popsicle® sticks. The debris comprised 0.54±0.69% on a wet mass basis (N = 48, median = 0.30%) and the maximum content measured was 3.1%. The debris-free food waste solids contents were similar in Phases III and IV and most of the solids were volatile (96±0.8% in Phase III and 94±2.6% in Phase IV). The pulping and dewatering process used at USAFA produced a food waste product that contained >20% TS.

Table 6. Average Food Waste and Digester Feed Characteristics.

Sample	Phase	TS	VS	COD	COD/VS[c]	Fat	Protein	Carbo-hydrate
		(% by mass)		(mg/L)	(mg/mg)	(% of dry organics)		
Undiluted Food Waste	III	26±2.8	25±2.8	-	-	20±10	38±17	42±21
Undiluted Food Waste	IV	22±6.1	21±5.9	320,000±82,000	1.6±0.2	-		
Undiluted Food Waste/Canola Oil Mixture[a]	III	29±2.6	28±2.7	-	-	28±8.5	32±17	40±19
Undiluted Food Waste/Canola Oil Mixture[a]	IV	25±6.0	24±5.8	390,000±80,000	1.7±0.1	-		
Digester Feed	III	9.2±1.3	8.9±1.3	120,000±29,000	1.2±0.2	-		
Digester Feed[b]	IV	25±6.0	24±5.8	390,000±80,000	1.7±0.1	-		

[a] By calculation
[b] Identical to undiluted food waste/canola oil mixture
[c] Calculated using paired data

5.5.2 Phases II and III

Organics Loading

Volumetric organic loading rates based on VS and COD were not met during Phase III (**Figure 12**). Loading rates were increased during Phase II (0–32 d). Further attempts to increase loading rates were not attempted during Phase III because the digesters were thought to be showing indications of stress and potential failure at the time. While pH was in a physiologically suitable range (7.8±0.1, see also **Figure 11**), the digester sludge was changing from a black to brown and the average ratio of VFA/TALK was somewhat high (0.15±0.09 mg-acetate equivalents/mg-calcium carbonate [$CaCO_3$]) though not greater than the goal of 0.2 mg-acetate equivalents/mg-$CaCO_3$. However, as discussed below, methane production continued, indicating the digesters had not failed in spite of these observations. SELR data (**Figure 12b**) provided a possible explanation as to why the organic loading rate could not be increased further during Phase III. The SELR increased during Phase II and averaged 0.44±0.17 kg-COD kg-VSS^{-1} d^{-1} during Phase III exceeding the goal of 0.26 kg-COD kg-VSS^{-1} d^{-1}. The average SELR was greater than the goal while the volumetric COD loading rate was less than its goal because the digester VSS concentrations were low and decreasing during Phase III (**Figure 13**). The SELR is equal to the volumetric COD loading rate divided by the VSS concentration in the digester. The VSS was quite low (7300±2000 mg/L) relative to typical anaerobic digesters that operate at a VSS concentration of ~15,000–30,000 (Tchobanoglous et al. 2003; Water Environment Federation 2010). This low and declining VSS concentration may have limited further increases in the volumetric organic loading rate to the digesters.

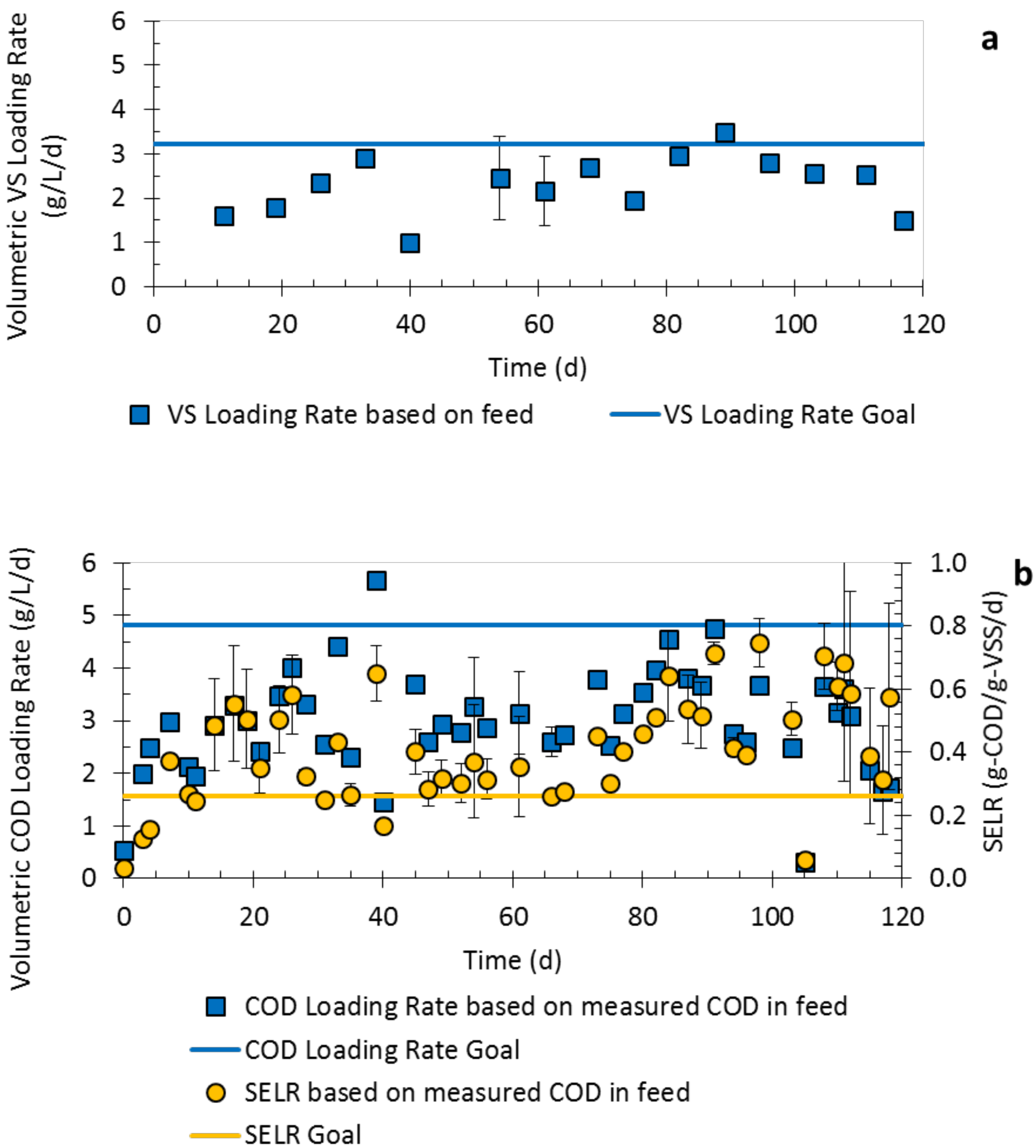

Figure 12. Volumetric VS Loading Rate (a) and Volumetric COD and SELRs (b) Compared to Goals.

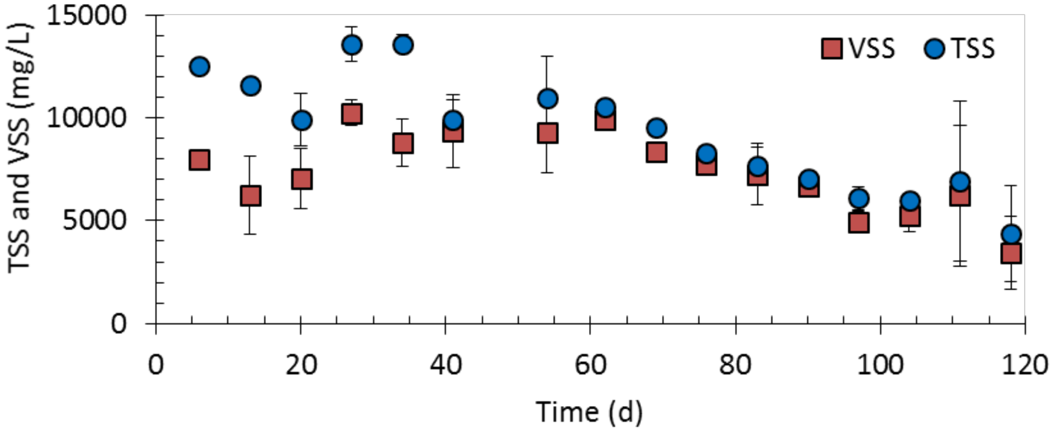

Figure 13. VSS and Total Suspended Solid (TSS) Concentration Trends During Phases II and III.

Methane Production

Both the biogas flow rate and the methane content in the biogas remained steady during Phase III (**Figure 14**) supporting the conclusion that the digesters were stable and not failing. Typically, one of the earliest indicators of anaerobic digestion failure is a sudden drop in biogas production and a decrease in the biogas methane content. Two spikes in biogas flow rate around 10 and 20 d were artifacts attributable to digester foaming and flow meter disturbance. Foaming was not observed thereafter.

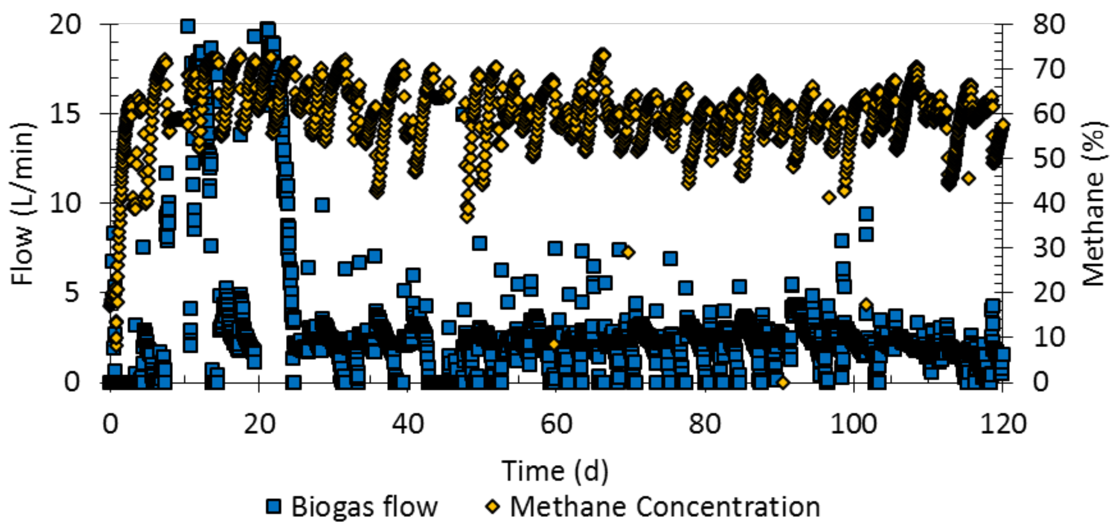

Figure 14. Biogas Flow Rate and Methane Concentration During Phases II and III.

While methane production was consistent throughout Phase III (**Figure 14**), the production rate of 0.82±0.22 liters of methane per reactor volume per day (L/L/d) was less than the goal of 2 L/L/d (**Figure 15**). The initially high rate on Day 6 was associated with the digester seed. It is likely that methane production was less than the goal because of the lower organic loading rate (COD and VS loading rates) as discussed earlier (**Figure 12**). Methane yields based on loaded COD and VS were 270±75 L/kg-COD and 360±70 L/kg-VS and exceeded the goals of 190 L/kg-COD and 310 L/kg-VS (**Figure 16**). This supports the conclusion that low organic loading rates to the digesters rather than inhibition limited the volumetric methane production rate.

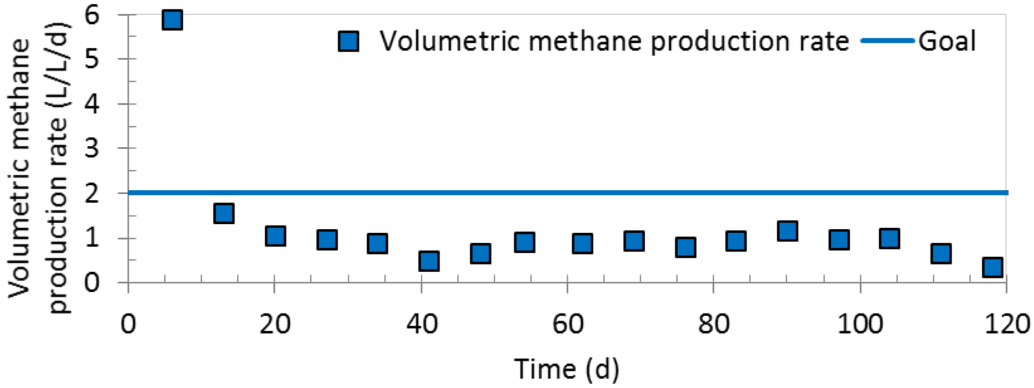

Figure 15. Volumetric Methane Production Rate during Phases II and III Compared to Goal.

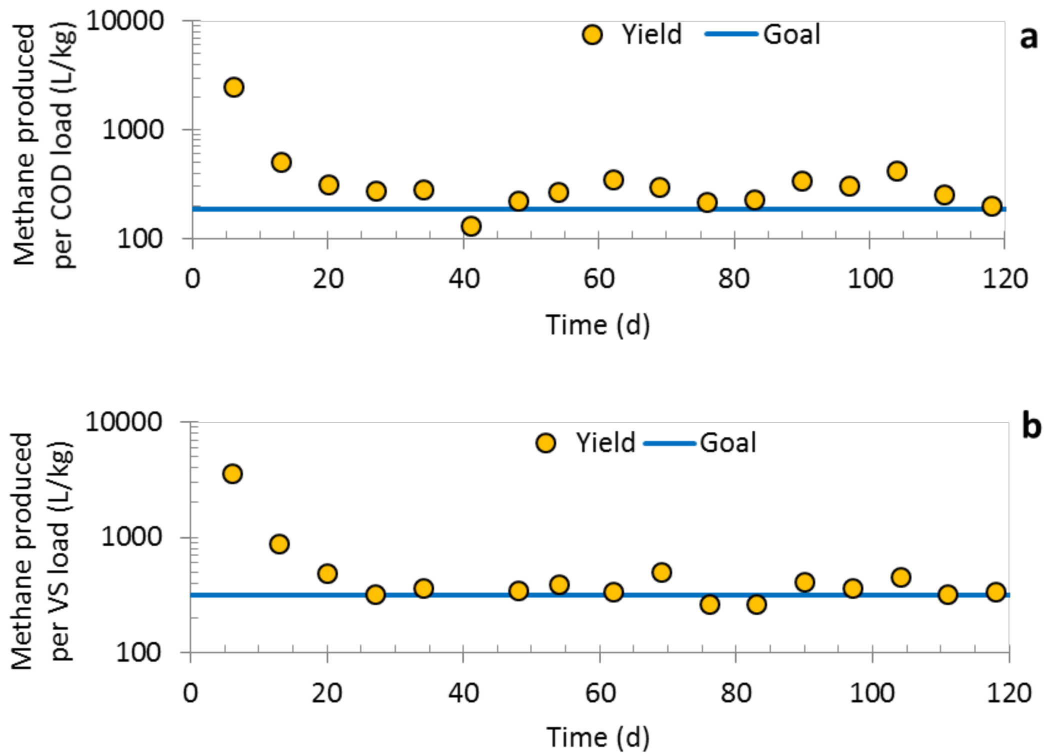

Figure 16. Methane Yield per Unit Loaded COD (a) and VS (b) During Phases II and III Compared to Goals.

Energy Conversion

Food waste energy conversion to methane was assessed by calculating the the total COD of the food waste/canola oil mixture fed to the digesters and the methane COD (377 mL-CH_4/g-COD at standard conditions of 21.4 ºC [70 ºF] for the biogas flow meter) generated each week (**Figure 17**). No discernable trends were observed indicating digester stability and the average energy conversion was 73±19%, which was about the same as the goal of 70%. This energy conversion did not consider parasitic demands (e.g., heating, pumping, and mixing) nor did it consider conversion of methane to electrical power. These aspects are discussed in Sections 6 and 7.

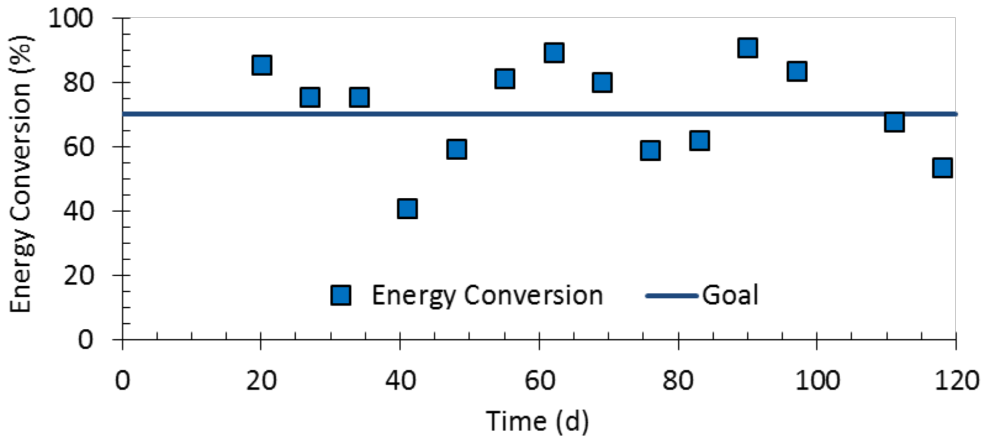

Figure 17. Energy Conversion Based on COD Loading and Methane Production During Phases II and III.

Energy conversion was also evaluated on a specific rate basis. The specific methane production rate was compared to the SELR to assess conversion of food waste energy (i.e., in terms of COD) to methane (**Figure 18**). The total specific methane production rate was less than the SELR (**Figure 18a**) and the slope of the correlation (**Figure 18a** inset) was 71% (intercept forced to 0, r^2 = 0.41), which is consistent with the observed energy conversion of 73±19%. Laboratory bench-scale BMP tests with USAFA food waste demonstrated that specific methane production per unit COD loaded was correlated to the protein+fat content. When the SELR was based only on protein+fat (**Figure 18b**), the energy conversion was 100% (intercept forced to 0, r^2 = 0.50). Additionally, the temporal variations in the specific methane production rate tracked the protein+fat SELR. These data suggest that methane production from the food waste/canola oil mixture was controlled by the fat+protein content. Additionally, these data indicate that measurement of fat+protein content is a potentially useful predictor of methane yield and production rate. Carbohydrates were apparently not digested as well as protein and fat. One hypothesis is that food waste carbohydrates include cellulosic materials that are relatively recalcitrant to biodegradation compared to protein and fat.

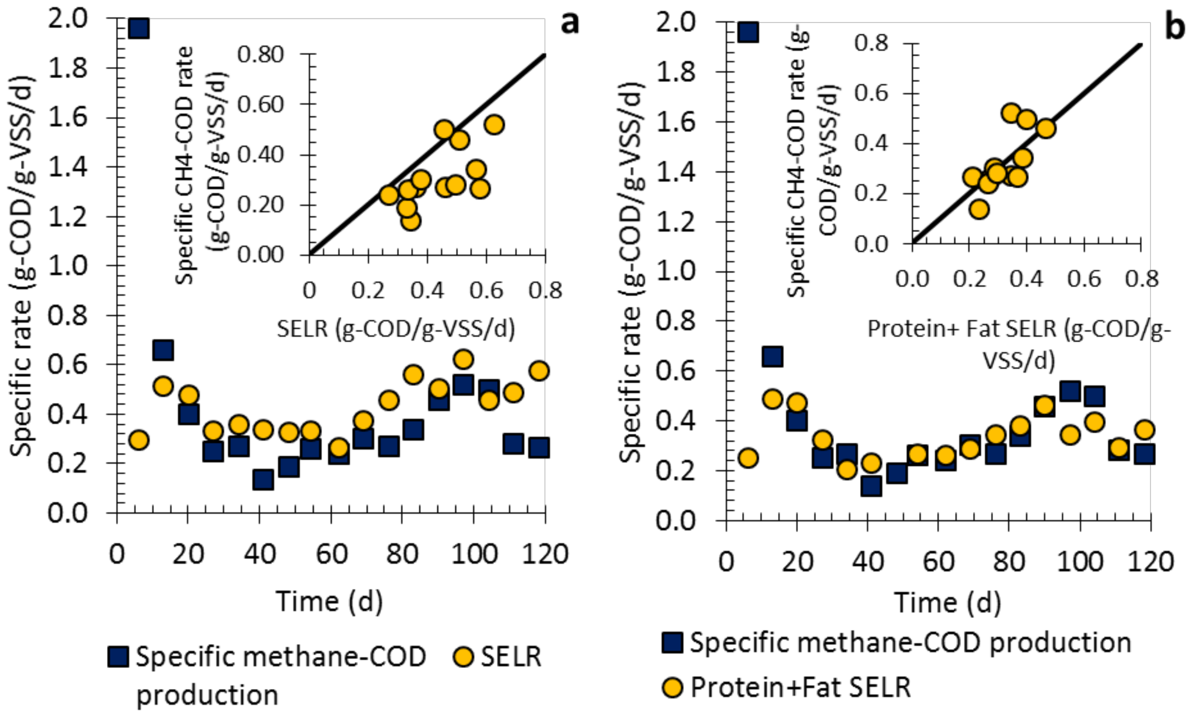

Figure 18. Specific Methane COD Production Rate Compared to Total SELR (a) and SELR Based on Protein+Fat Content (b).

High methane production on Day 6 is attributable to the digester seed. Insets show data from Phase III (≥33 d) and line of unity.

The energy efficiency of 73±19% calculated above, does not take into account parasitic energy losses incurred during conversion of biogas energy into usable power. Conversion efficiencies were calculated to assess the actual performance of the pilot digester and theoretical conversion of biogas to compressed biomethane capable of being used for vehicle fueling. Parasitic losses and net energy performance criteria were calculated for a nominally sized digester (i.e., 1 million gal), which would be capable of handling 100 tons/d (95,000 kg/d) of food waste based on the above results. Typical pumping flow rates, pump heads, and gas scrubbing compressor energies were estimated or assumed as described in the Final Report. The energy efficiency accounting for parasitic demands was calculated to be 63%, which is near the goal of ≥50%.

Solids Destruction

High percentages of TS and VS destruction were observed (**Figure 19**). The average total solid destruction (TSD) and volatile solid destruction (VSD) were 78±3.4% and 81±3.0%, respectively. The observed TSD and VSD were >~55% typically observed for waste activated sludge (Water Environment Federation 2010; Tchobanoglous et al. 2003) and similar to values previously reported for food waste (Gray [Gabb] 2008). The TSD and VSD results were greater than the goals of 60% and 38%, respectively. Volatile suspended solids destruction (VSSD) was calculated as an estimate of the reduction of food waste solids to digester sludge that may require subsequent

disposal. The VSSD result of 92±2.7% indicates high food waste reduction can be achieved by anaerobic digestion.

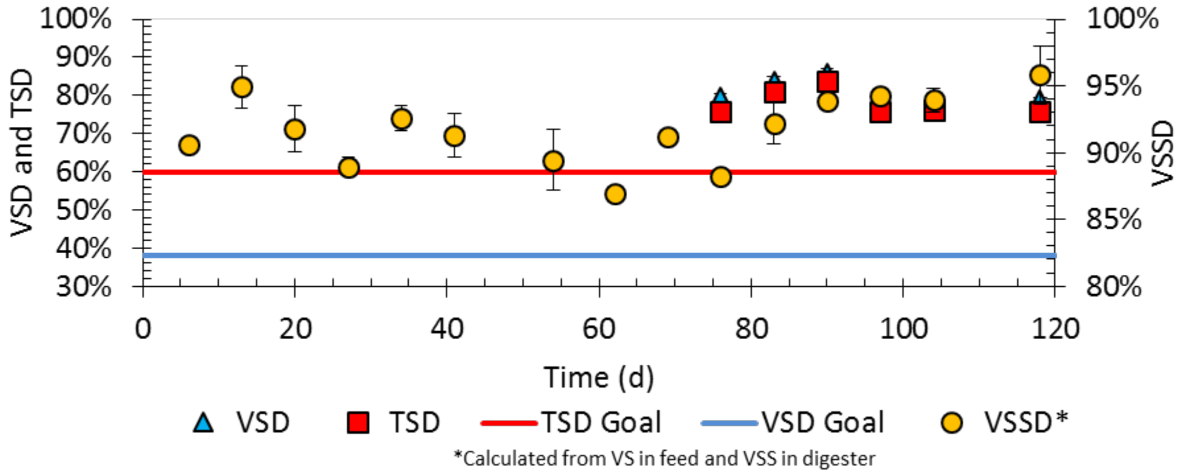

Figure 19. VSD and TSD Compared to Goals.

VSSD is also shown, which was calculated from VSS in the digestate and VS in the digester feed.

5.5.3 Phase IV

At the conclusion of Phase III, the pilot digesters were drained, the feeding process was modified to eliminate food waste/canola oil dilution with water, and one digester was reseeded to initiate Phase IV. Digestate was used to mix and dilute the food waste/canola oil instead of potable water. Phase IV did not have a startup or acclimation step analogous to Phase II. The SRT and hydraulic retention time (HRT) were longer than in Phase III (i.e., 130±91 d versus 40±14 d) because of the more concentrated food waste/canola oil mixture digester feed. The duration of Phase IV was <1 SRT and the digester was not considered to have reached steady state.

The volumetric VS and COD loading rates and the SELR are presented in **Figure 20**. The loading rates were kept relatively constant for the first 20–30 d and were increased in excess of the goals. The modified feeding strategy resulted in the volumetric VS and COD loading rates (2.9±0.8 g-VS/L/d [goal = 3.2] and 5.3±1.8 g-COD/L/d [goal = 4.8]) possibly being met during the last 20 d of Phase IV considering data variability. The Phase IV SELR was similar in Phase IV (0.47±0.30 g-COD/g-VSS/d) to that in Phase III (0.44±0.17 g-COD/g-VSS/d).

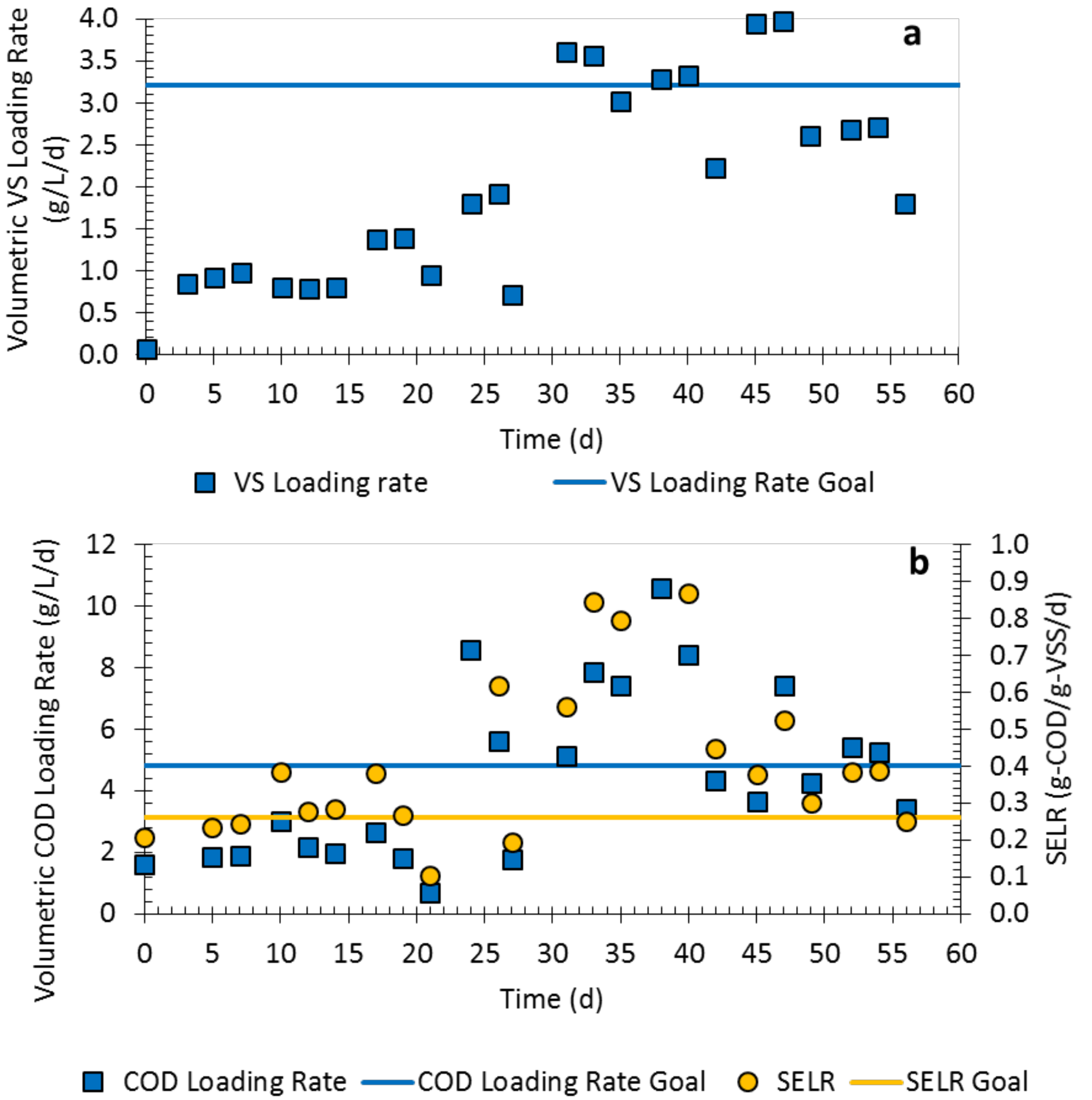

Figure 20. Phase IV Volumetric VS (a) and COD Loading Rates (b) and SELR (b) Compared to Goals.

The modified feeding strategy clearly had the desired effect of increasing TSS and VSS over time (**Figure 21**) in contrast to the decreasing trend observed during Phase III (**Figure 13**). The increased VSS presumably was associated with a greater and more robust microbial population that allowed the volumetric methane production rate goal of 2 L/L/d to be achieved at the end of Phase IV (**Figure 21**). Digester operation was stopped at this time and, thus, stability of the methane production rate could not be determined. Nevertheless, a clear increasing trend was observed demonstrating the value of the concentrated food waste feeding strategy.

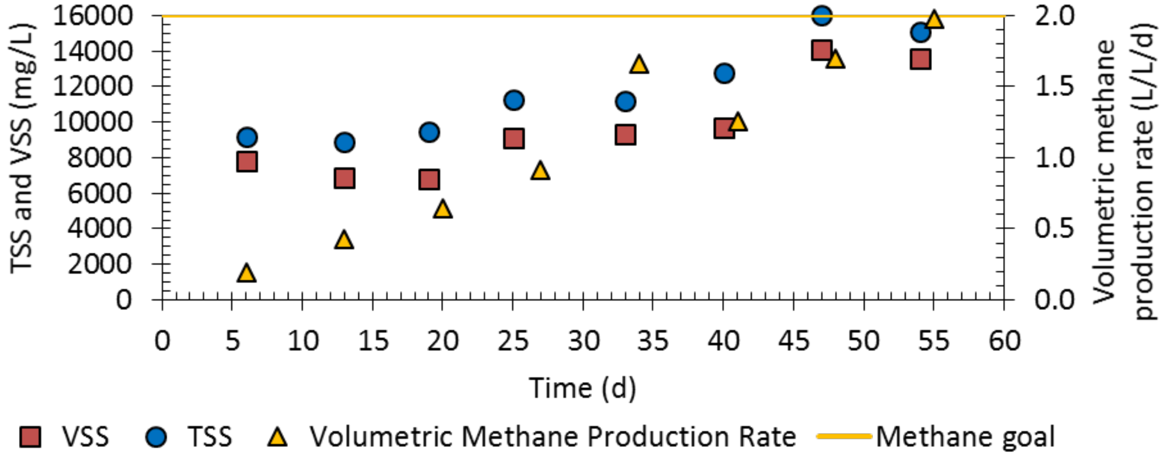

Figure 21. Phase IV Trends of Solids and Volumetric Methane Production Rate Compared to Goal.

Residuals

The digestates in Phase III and IV were analyzed for various parameters that are related to potential reuse (e.g., as fertilizer or compost amendment) or disposal. **Table 7** summarizes the results of testing. The results reported for Phase IV are for single grab sample collected on Day 54 of Phase IV. In addition, Dr. Matt Higgins of Bucknell University conducted dewatering tests on a sludge sample at the end of Phase IV. The sludge was not easily dewatered and the resultant cake solids were 9.5%. The poor dewaterability was attributed to the high ratio of monovalent cations (e.g., ammonium) to divalent cations (e.g., calcium).

Table 7. Digestate Analysis Results.

Analyte	Units	Result	Regulatory Limit[a]
Total COD	mg/L	30,000	NA
TSS	mg/L	15,000	NA
VSS	mg/L	14,000	NA
Total ammonia	mg-N/L	2,500	NA
Total alkalinity (TALK)	mg-$CaCO_3$/L	12,000	NA
pH	--	7.73	NA
Heterotrophic plate count (HPC)	CFU/mL	6.6E+07	NA
Fecal coliforms	MPN/100 mL	4.9E+04	NA
Sulfide	mg/L	71	NA
Arsenic	µg/L	<100	5,000
Barium	µg/L	25,700	100,000

Analyte	Units	Result	Regulatory Limit[a]
Cadmium	µg/L	15	1,000
Chromium	µg/L	146	5,000
Cobalt	µg/L	392	NA
Copper	µg/L	3,660	NA
Iron	µg/L	42,300	NA
Lead	µg/L	<100	5,000
Manganese	µg/L	1,250	NA
Mercury	µg/L	1.52	200
Molybdenum	µg/L	764	NA
Nickel	µg/L	499	NA
Selenium	µg/L	260	NA
Silver	µg/L	24	5,000
Zinc	µg/L	7,140	NA

[a] RCRA toxicity characteristic for hazardous wastes.
CFU – colony-forming unit, MPN – most probable number, N/L – nitrogen per liter, µg/L – microgram(s) per liter

The follow general conclusions can be made regarding digestate quality:

- COD concentration of the digestate was high in part because of the high VFA concentrations. The VFA concentrations also resulted in the digestate having a strong odor.
- TSS and VSS concentrations were moderate and would likely be greater with prolonged operation at high solids loading in the feed.
- Dewatering the sludge was challenging.
- Ammonia was high, indicating good potential as a nutrient source.
- Metals were less than the Resource Conservation and Recovery Act (RCRA) toxicity characteristic for designating hazardous waste. However, this regulatory criterion is not necessarily applicable to this sludge if it is regulated under the Clean Water Act. Certain metals (i.e., Co, Mo, Ni, and selenium [Se]) were present because they were added to the food waste as nutrients. Others may have originated either from the digester seed or the food waste.

5.5.4 Biogas Characterization and Purification

Biogas Characterization

Methane content of the digester biogas was 59±4.6% and 61±6.6% in phases III and IV, respectively. These results are equivalent to the goal of 60%. Digester biogas concentrations of H_2S were 2,500±1,100 mg/cubic meter (m^3) (1,800±780 parts per million [ppm]) and 2,000±590 mg/m^3 (1,400±420 ppm) in phases III and IV, respectively.

Sulfur Removal

During Phase IV, SulfaTrap™ was evaluated for H_2S removal from digester biogas and VSA was evaluated for CO_2 and moisture removal. On Day 14, 2.3 kg of SulfaTrap™ was installed into the gas purification system; **Figure 22** illustrates the performance with respect to H_2S removal. H_2S concentrations were reduced by 99.9% or more until breakthrough around 50 d. H_2S concentrations prior to breakthrough averaged 0.11±0.14 ppm (0.16 mg/m^3). The sulfur content of the spent SulfaTrap™ was 3.9% by weight. This is considerably less than the expected loading of >20%. The reason for the lesser performance was moisture condensation on the SulfaTrap™ media based on visual observation. Moisture condensation affects sulfur loading capacity and mass transfer. Condensation would be prevented in a full-scale application by maintaining biogas at a temperature above its dew point.

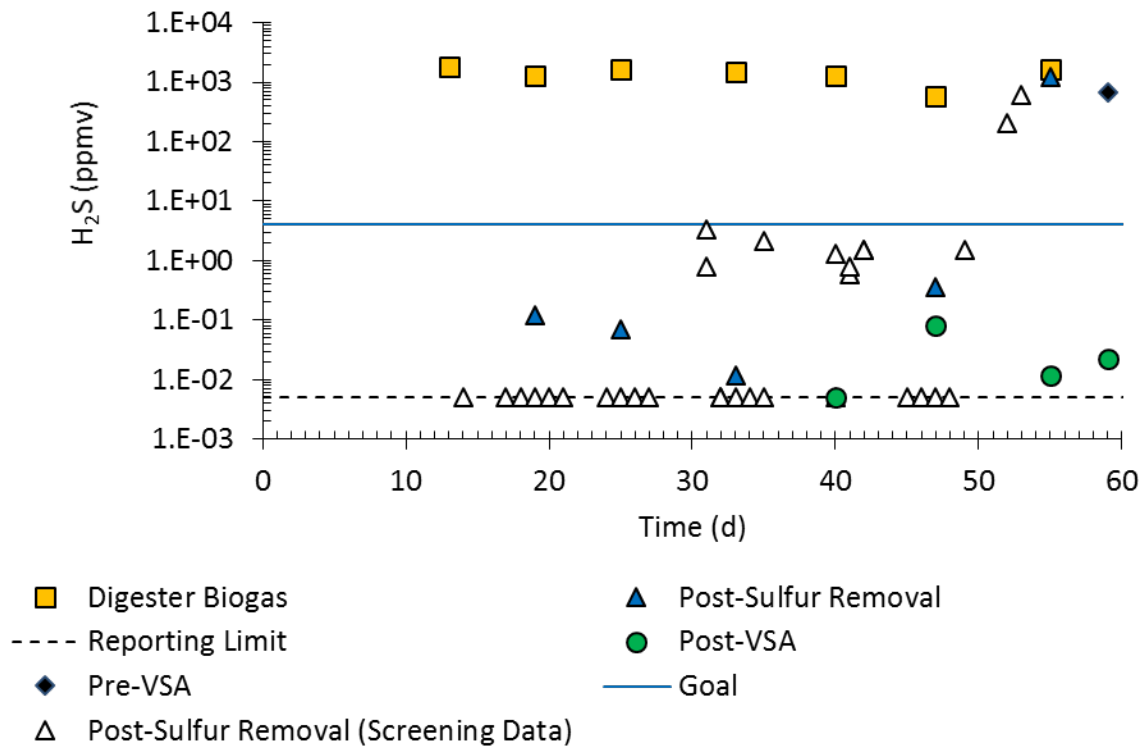

Figure 22. H_2S Removal by SulfaTrap™ Installed on Day 14 and VSA Operated Starting on Day 40.

The Pre-VSA sample was collected from the biogas holder to provide a direct measurement of the VSA inlet concentration.

Carbon Dioxane and Moisture Removal

Biogas that has been desulfurized (sweetened) was stored in a biogas holder prior to treatment by the VSA. **Table 8** presents a summary of post-VSA gas composition and characteristics in comparison to natural gas specifications. In general, the goals for natural gas quality were met.

Nitrogen and oxygen measurements were compromised by accidentally introduced air during grab sampling. This conclusion is supported by the ratio of oxygen to nitrogen of 39±7%, which is similar to, though slightly higher than, that for air (27%). Methane recovery was estimated to be 94±2.9% exceeding the goal of 80%.

Table 8. Post-VSA Gas Composition and Properties.

Parameter	Post-VSA	Natural gas specification
H_2S	0.030±0.035 ppmv	<4 ppmv
CH_4 [a]	98±0.5%	≥95%
CO_2 [b]	2.1±0.4%	<3%
N_2 [c]	3.1±2.0%	<3%
O_2 [c]	1.2±0.6%	<0.2%
Moisture content	0.10 g/m^3 (6 lb/MMscf) [d]	<0.12 g/m^3 (<7 lb/MMscf)

[a] Result is corrected for air accidentally introduced into the samples during grab sampling. Uncorrected result is 94±2.9%.

[b] Online infrared analysis indicated CO_2 was <1.5%.

[c] Not corrected for sampling artifact.

[d] Equivalent to a dew point of -40 ^oC

g – gram(s), MMscf – millions of standard cubic feet, ppmv – parts per million by volume

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6.0 PERFORMANCE ASSESSMENT

This section provides a detailed synthesis of the data presented in Section 5 with the Technology Performance Objectives presented in Section 3. Several of the Quantitative and Qualitative Performance Objectives are related and are discussed together below.

6.1 RENEWABLE ENERGY CONVERSION

Renewable energy conversion was evaluated with respect to: (1) energy conversion efficiency, (2) methane yield, (3) methane production rate, and (4) biogas methane content.

The energy conversion efficiency was first evaluated by comparing methane produced by the digester to the food waste and canola oil loaded. The average energy conversion in Phase III was 73±19% (**Figure 17**) and was similar to the goal of ≥70% though not exceeding it. The energy efficiency reported above does not take into account parasitic losses including pumping, digester heating, and conversion of biogas energy into usable power such as compressed natural gas for vehicle fueling. When these losses are taken into account, the energy efficiency for Phase III was estimated to be 63%, which exceeded the goal of ≥50%.

The methane yields based on VS loading in Phases III and IV were 360±70 L/kg and 490±140 L/kg, respectively. These yields were greater than the goal of 310 L/kg. The methane yields based on COD loading in Phases III and IV were 270±75 L/kg and 230±150 L/kg, respectively. These yields were greater than the goal of 190 L/kg. The volumetric methane production rate goal of 2 L/L/d was not met in Phase III. During this phase, 0.82±22 L/L/d was produced (**Figure 15**) and was limited by the organic loading rate as discussed in Section 6.2. Phase IV involved modification of the food waste/canola oil feeding strategy to eliminate water addition and effectively feed a more concentrated food waste/canola oil mixture. This modification resulted in greater VSS concentrations (compare **Figures 13** and **21**) and presumably greater microbial concentrations, which in turn allowed greater organic loading rates. The net effect was gradually increasing volumetric methane production rates over the 59-d Phase IV operational period ultimately producing 2.0 L/L/d (**Figure 21**).

Biogas composition in Phases III and IV were 59±4.6% and 61±6.6%, respectively, and near the goal of 60%. Typical methane concentrations in digester biogas range from 59% to 64% (Tchobanoglous et al. 2003; Water Environment Federation 2010).

In addition, the yield and rate of methane production was determined to be correlated to the protein+fat content of the food waste (**Figure 18**). These observations suggests a useful metric for prediction of methane production from food waste and FOG. The observations also suggest the carbohydrate fraction of USAFA food waste was relatively recalcitrant. Recalcitrance to biodegradation may have been caused by the carbohydrate fraction being comprised predominately of cellulose (e.g., roughage or fiber) as opposed to starch and simple sugars.

The following conclusions can be made regarding the energy conversion performance objective:

- Energy efficiency of the food waste digestion process met but did not exceed the goals of 70% for food water/canola oil COD conversion to methane. The goal of 50% considering parasitic power losses was exceeded.
- Methane yields based on VS and COD loading were exceeded reflecting the high digestibility of the food waste.
- The protein+fat fraction can be used to predict methane production rate and potentially methane yield.
- The methane content of the biogas was consistent (~60%) though it did cycle in response to cyclic feeding. Continuous feeding would dampen this cycling.

6.2 DIGESTER CAPACITY/STABILITY

Digester capacity and stability was evaluated with respect to: (1) volumetric VS and COD loading rates, (2) SELR, (3) pH, (4) VFAs and the ratio VFA/TALK, (5) ammonia and potential toxicity, and (6) food waste/canola oil composition.

The Phase III volumetric VS (2.4±0.6 g-VS/L/d) and COD (3.0±1.0 g-COD/L/d) loading rates (**Figure 12**) were less than the goals of 3.2 g-VS/L/d and 4.8 g-COD/L/d. Attempts to increase loading further between the start of Phase III on Day 33 and Day 100 were not made because of several observations that suggested digester inhibition and potential for failure. On the other hand, pH during Phase III was not inhibitory (7.8±0.1). Inhibition was later determined to not have occurred as described in the Final Report (Evans et al. 2016).

The laboratory study provided initial evidence that a diluted digester feed could lead to digester instability. Previous research has suggested that close associations between syntrophic bacteria and methanogens promotes development of microenvironments that promote more rapid digester startup and stability (McMahon et al. 2004). Based on these results, it was hypothesized that dilute VSS concentrations and associated dilute concentrations of syntrophic bacteria and methanogens could lead to instability. The VSS concentration at the end of Phase III was 3,500±1,800 mg/L (**Figure 13**). This low VSS concentration was likely associated with low microbial concentrations, which would limit the achievable and sustainable volumetric organic loading rate to the digesters. The SELR was used to evaluate organic loading relative to the low VSS.

The Phase III SELR was 0.44±0.17 g-COD/g-VSS/d (**Figure 12**), which exceeded the goal of 0.26 g-COD/g-VSS/d. Assuming a VSS concentration of 2% in an anaerobic digester treating waste activated sludge and a COD/VS ratio of 1.8 g/g, the SELR goal translates to a volumetric VS loading rate of 2.9 g-VS/L/d (0.18 lb/ft^3/d), which is near the maximum at which anaerobic digesters are typically loaded (Tchobanoglous et al. 2003; Water Environment Federation 2010). The observed value of 0.44±0.17 g-COD/g-VSS/d is 70% greater than the goal, suggesting that the organic loading was at risk of exceeded the metabolic capacity of the microorganisms in the digester. However, the capacity was not exceeded based on the observed methane yields and production rates. Furthermore, the specific methane production rate was observed to correlate to the protein+fat SELR (**Figure 18**).

One way to increase the volumetric organic loading rate to the digester is to increase the VSS concentration. Phase IV evaluated this approach where the digester feeding process was modified to eliminate dilution water. Digestate was recycled only to create a pumpable food waste/canola oil slurry. The effective VS of the food waster/canola oil mixture fed to the digesters in Phases III and IV were 8.9±1.3% and 24±5.8%, respectively—an increase of 170%. This process change achieved the desired goal of increasing VSS concentrations in the digester. The VSS concentrations at the end of Phases III and IV were 3,500±1,800 mg/L (**Figure 13**) and 14,000 mg/L (**Figure 21**), respectively, even though the starting VSS concentrations were both 7,800 mg/L. With the increase in VSS, the volumetric organic loading rate (**Figure 20**) and methane production rate (**Figure 21**) increased compared to Phase III (**Figures 12** and **15**). The SELR did not increase (0.47±0.30 g-COD/g-VSS/d in Phase IV versus 0.44±0.17 g-COD/g-VSS/d in Phase III) providing additional justification for the SELR concept.

The following conclusions can be made regarding the digester capacity/stability performance objective:

- Volumetric organic loading rates for VS and COD were not met on average but were met near the end of Phase IV as a result of the feeding process modification.
- Feeding a concentrated food waste/canola oil mixture (e.g., 24±5.8% VS) in Phase IV resulted in the ability to increase organic loading rates and methane production rates. Feeding this concentrated mixture did lead to a long SRT (130±91 d) but this Phase did not operate sufficiently long (i.e., 0.45 SRT) to obtain steady state data.
- The SELR was a practical parameter that normalized volumetric organic loading rates to food wastes with varying energy contents (i.e., protein, fat, and carbohydrates) and to the VSS and associated microbial content in the digester. A value of 0.4 g-COD/g-VSS/d was considered to be a reasonable maximum design value that allows stable digester operation.
- Free ammonia concentrations of 160 milligrams of nitrogen per liter (mg-N/L) and potentially greater were not inhibitory (Evans et al. 2016).
- Food waste/canola oil digestion was stable even though normal indicators of instability (e.g., high VFA concentrations, high VFA/TALK, brown sludge) were observed.

6.3 WASTE SLUDGE RESIDUALS

Waste sludge residuals were evaluated with respect to: (1) solids destruction, and (2) physical, chemical, and biological characteristics relevant to reuse or disposal.

In addition to energy recovery, solids destruction and minimization of solid waste generation is a goal of food waste digestion. TSD and VSD in Phase III were 78±3.4% and 81±3.0%, respectively, compared to goals of 60% and 38%. The Phase III measured values include both suspended and dissolved solids fractions. Therefore, they do not represent the amount of sludge (i.e., undissolved solids) destruction. Calculation of sludge destruction was conducted by comparing the VSS of the digestate to the VS of the food waste/canola oil mixture. In doing this calculation, the food waste/canola oil solids were assumed to be completely undissolved. The result, defined as the VSSD, was 92±2.7%. The value for TSSD was 91±2.8%. Therefore, the anaerobic digestion process was capable of reducing solid waste generation by 90%.

Biosolids generated by the process are regulated under 40CFR503(b), which provides definitions for two classes of biosolids: Class A and B. Class B is relevant to this demonstration and requires a 15-d SRT and 38% VSD. The SRT for Phase III was 40±14 d. Therefore, the digestion process met the requirements for Class B biosolids. These regulation as typically applied to waste-activated sludge from a municipal WWTP. Therefore, these regulations may not be directly applicable to food waste digestion. Class A would require digestion at higher temperatures (i.e., thermophilic) and associated pathogen destruction. This was not evaluated but is a possible approach to food waste digestion.

The following conclusions can be made regarding residuals from the process:

- The digestate contained high concentrations of ammonia (2,500 mg-N/L) and various metal nutrients indicating it has high potential for use as a liquid fertilizer. The ammonia concentration can be highly variable and will depend on the protein content of the food waste feed. Some of the metals (Co, Mo, Ni, and Se) were added because the food waste was deficient with respect to sustained methanogenesis.
- The solids content was low (1.5%) and these solids were difficult to dewater. These aspects may provide challenges with respect to handling, but the addition of a source of divalent cations (e.g., lime) may promote better dewaterability.
- Microbial pathogens (i.e., fecal coliforms) were present, which may require special handling if used as a liquid fertilizer.
- No hazardous characteristics (e.g., hazardous metals in excess of RCRA toxicity characteristics) were observed that would prohibit disposal. However, sulfide was present as well as VFAs, which can create a human health exposure (i.e., H_2S) and an odor issue. These attributes may affect its acceptability as a compost supplement or a liquid fertilizer.

6.4 GAS PURIFICATION

Gas purification was evaluated with respect to: (1) biogas composition, (2) H_2S removal, (3) CO_2 and moisture removal, and (4) potential renewable energy uses.

The biogas contained typical concentrations of methane (59±4.6% in Phase III) and H_2S (2,500±1,100 mg/m^3 [1,800±780 parts per million by volume (ppmv)] in Phase III). The H_2S was removed by >99.9% by the SulfaTrap™-R7 adsorbent but sulfur loading was less than expected (3.9% versus >20%) because of moisture condensation on the SulfaTrap™ media. Laboratory studies conducted by TDA with simulated biogas demonstrated sulfur loadings >20%. A full-scale system would be designed to prevent moisture condensation.

The VSA system was capable of recovering 94±2.9% methane compared to the goal of 80%. Treated gas met all natural gas specifications with the exception of oxygen and nitrogen content. However, sample contamination with air appears to have compromised sample results. Therefore, the system was likely capable of generating natural gas that could be compressed for vehicle fueling or injection into a natural gas pipeline.

6.5 GHG ACCOUNTING

The food waste digestion/biogas purification process has the potential to offset GHG emissions by: (1) minimizing methane emissions from landfills, and (2) decreasing fossil fuel-derived CO_2 emissions that are generated via electricity production and vehicle use. A comparison of the food waste digestion/biogas purification process to current methods of food waste management (i.e., landfilling and composting) was conducted.

GHG documentation was based on projected emissions from a nominally sized digester (i.e., 1 million gal). This digester would be capable of handling 100 tons/d (95,000 kg/d) of food waste based on demonstration results. This digester is clearly oversized for most installations but the results from calculations can be scaled to smaller facilities. The calculations assume that the facility operates at a 40-d SRT, produces 270 L of methane/kg COD fed (from study results), and is fed 120,000 mg/L COD (based on study food waste characteristics). Calculations were also based on 94% methane recovery by the VSA process. Power for the process were estimated. Electrical power was assumed to emit 1.34 lb of CO_2/kilowatt hour (kWh) electricity consumed (Energy Information Administration 2002).

The calculated GHG emissions from a food waste digester is -470 tons/year (yr) (i.e., a GHG offset). By comparison, previous research demonstrated that the GHG emissions from landfilling and composting were 0.15 and 0.05 kg carbon dioxide equivalent (CO_2e)/kg food waste (Parry 2012). Using the food waste characteristics of this study, this would be an equivalent of 530 and 180 tons/yr for landfilling and composting, respectively. Thus, food waste disposal in anaerobic digesters represents a significant GHG savings compared to landfilling and composting.

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7.0 COST ASSESSMENT

This study has shown that food waste digestion is technologically viable. The study showed that the anaerobic digestion process reduced food waste solids and the biogas could be purified for use as compressed natural gas. This section examines the economic viability of the process.

7.1 COST MODEL

To assess the economic viability, a simple cost model has been developed. The model utilizes study performance conclusions including solids destruction, methane production, food waste characteristics, and SELR, as well as published information for per capita food waste generation to estimate the size of a full-scale food waste digestion system. This will be done at three different base sizes—net base sizes of 10,000, 20,000, and 40,000 personnel. Utilization of the methane fuel was evaluated for the following technologies: heat production in boilers, combined heat and power (CHP) production, biomethane production for pipeline quality natural gas, and biomethane production for vehicle fuel. A White Paper prepared early in this study demonstrated that vehicle fuel can be the most cost-effective use of biomethane generated from food waste digestion (Evans et al. 2016).

Costs of the digestion facility and sub-facilities for biogas methane production were estimated based on published information, equipment quotes (adjusted to particular appropriate sizes), and engineering judgment.

7.1.1 Full-Scale Anaerobic Digestion Facilities

Facilities for bases of 10,000, 20,000, and 40,000 personnel were determined. Designs assumed a TS waste generation rate of 2 kg/capita/d with a food waste fraction of 14.5% of the total municipal solid waste discarded (USEPA 2012). Thus, the per capita food waste generation rate was 0.29 kg/capita/d.

Capital costs for the anaerobic digestion system were calculated using CDM Smith engineering cost curves. These curves were developed from many WWTP digesters based on volume of the digestion facility. The costs are full costs including tankage, pumping equipment, boilers, and flares. The costs include contractor markups, mobilization, equipment startup, and demobilization. The costs do not include engineering services. An additional 25% was added onto the construction costs to cover engineering and construction management services. Anaerobic digester facilities were assumed to be constructed of concrete.

Based on the size of the digesters and the cost curves, the projected costs of the digester system are as follows:

- 10,000 personnel base, $0.5 million
- 20,000 personnel base, $0.8 million
- 40,000 personnel base, $1.4 million

Power draw for digestion equipment was calculated as follows:

- 10,000 personnel base, 10 kilowatts (kW)
- 20,000 personnel base, 12 kW
- 40,000 personnel base, 15 kW

7.1.2 Gas Utilization Facilities

Methane gas generated from the anaerobic digestion facilities is a beneficial fuel. Most commonly, the fuel is used for one of four basic purposes: (1) production of heat, (2) production of heat and power, (3) as a natural gas substitute, or (4) as a vehicle fuel (in the form of compressed natural gas). All alternatives were assumed to include hot water boilers for heat production as the heat is needed to maintain the anaerobic digestion process. However, the heat was assumed to have no value as many locations do not have a demand for heat beyond the anaerobic digestion process. At the methane lower heating value of 36 megajoules (MJ)/m^3 and typical engine efficiencies of 38%, the power production ranges are estimated as follows:

- 10,000 personnel base, 33 kW
- 20,000 personnel base, 67 kW
- 40,000 personnel base, 133 kW

The size of the expected power production is less than those of typical internal combustion engines. As such, CHP through the traditional engine would likely not be effective. However, the power production aligns with typical microturbines. Therefore, it is assumed that any CHP solution would utilize microturbines. Projected costs for CHP microturbines have been documented (Darrow et al. 2015). Based on this document, the expected project costs for a microturbine installation are as follows:

- 10,000 personnel base, $160,000
- 20,000 personnel base, $240,000
- 40,000 personnel base, $480,000

In addition to CHP, the biogas can be scrubbed to natural gas quality. Once scrubbed to natural gas quality, it can be injected into a natural gas line as a natural gas substitute or compressed to high pressures and used as a vehicle fuel. The cost of a vehicle fueling station was based on published data (Smith and Gonzales 2014). Based on this document, the cost of a fast-fill filling station is estimated as follows:

- 10,000 personnel base, $270,000
- 20,000 personnel base, $510,000
- 40,000 personnel base, $640,000

Treatment of the raw biogas to natural gas quality require that all contaminants, moisture, sulfur, and CO_2 are removed. **Table 9** presents the different gas purification and utilization systems with

the appropriate gas treatment technology. Note that for vehicle fuel, the system was analyzed comparing both the TDA VSA and a water scrubber system.

Table 9. Comparison of Various Gas Purification Systems.

Utilization	Sulfur Removal	Moisture Removal	CO_2 Removal	Delivery Pressure (kPa gauge)
CHP using a microturbine	Not required	Gas chiller	Not Required	517
Injection into natural gas pipeline	Iron sponge	VSA	VSA	103
Vehicle fuel –VSA	SulfaTrap™	VSA	VSA	24,800
Vehicle fuel – water scrubber	Water scrubber	Gas chiller	Water Scrubber	24,800

kPa – kilopascal(s)

Project costs are estimated to be two times the equipment cost for construction and installation, plus another 25% for engineering. Thus, the costs for the gas treatment options were calculated as follows:

- Moisture removal
  - 10,000 personnel base, $30,000
  - 20,000 personnel base, $40,000
  - 40,000 personnel base, $70,000
- Iron sponge
  - 10,000 personnel base, $120,000
  - 20,000 personnel base, $170,000
  - 40,000 personnel base, $260,000
- SulfaTrap™
  - 10,000 personnel base, $40,000
  - 20,000 personnel base, $50,000
  - 40,000 personnel base, $80,000
- Water Scrubber
  - 10,000 personnel base, $130,000
  - 20,000 personnel base, $190,000
  - 40,000 personnel base, $290,000

- VSA
  - 10,000 personnel base, $140,000
  - 20,000 personnel base, $210,000
  - 40,000 personnel base, $320,000
- Gas compressors for natural gas line pressure
  - 10,000 personnel base, $130,000
  - 20,000 personnel base, $140,000
  - 40,000 personnel base, $150,000
- Gas compressors for microturbines
  - 10,000 personnel base, $230,000
  - 20,000 personnel base, $240,000
  - 40,000 personnel base, $250,000
- Gas compressors for vehicle fuel were included in the vehicle fueling station

Gas treatment systems were assumed to have the following power drawing equipment:

- Moisture removal (based on saturated gas at the flowrates)
  - 10,000 personnel base, 0.5 kW
  - 20,000 personnel base, 0.9 kW
  - 40,000 personnel base, 1.7 kW
- Iron sponge technique and SulfaTrap™, no electrical draw
- Water scrubber
  - Water circulation
    - 10,000 personnel base, 4 kW
    - 20,000 personnel base, 7 kW
    - 40,000 personnel base, 14 kW
  - Gas pressurization, not included as water scrubber paired only with vehicle fuel option that requires pressures in excess of the water scrubber pressure.
  - Tail gas treatment, in a biofilter
    - Assumed at 5 kW for all sizes

- VSA
  - 10,000 personnel base, 4 kW
  - 20,000 personnel base, 7 kW
  - 40,000 personnel base, 15 kW

- Pressurization to natural gas line pressure, assumes adiabatic compression
  - 10,000 personnel base, 0.3 kW
  - 20,000 personnel base, 0.7 kW
  - 40,000 personnel base, 1.3 kW

- Pressurization for microturbines, assumes adiabatic compression
  - 10,000 personnel base, 1 kW
  - 20,000 personnel base, 2 kW
  - 40,000 personnel base, 4 kW

- Pressurization to vehicle fuel pressures, assumes isothermal compression with water cooled compressors.
  - 10,000 personnel base, 5 kW
  - 20,000 personnel base, 10 kW
  - 40,000 personnel base, 19 kW

In addition to power costs, the operation of gas treatment will be impacted by chemical/sorbent/media costs as well as operations and maintenance (O&M) costs.

The iron sponge and VSA systems are projected to have a consumable cost. The consumable cost projections for these technologies are as follows:

- Iron sponge, media replacement cost, based on $1.76/lb of iron sponge media
  - 10,000 personnel base, $7,000
  - 20,000 personnel base, $14,000
  - 40,000 personnel base, $28,000

- VSA
  - 10,000 personnel base, $2,000
  - 20,000 personnel base, $2,000
  - 40,000 personnel base, $4,000

Projected operating costs for SulfaTrap™ were estimated at \$41.31/kg of sulfur, which equates to the following costs:

- SulfaTrap™
  - 10,000 personnel base, \$17,000
  - 20,000 personnel base, \$35,000
  - 40,000 personnel base, \$70,000

The projected labor requirements for the gas treatment systems are as follows:

- Moisture removal, labor is assumed to be 1 hour (hr)/d
- Iron sponge, typical labor is 1 hr/d, plus media change out of 40 hr for one week of the year
- SulfaTrap™, typical labor is 12 hr/replacement with replacement occurring 2/yr
- Water scrubber, typical labor of 2 hr/d, plus media cleaning 4 times/yr at 40 hr/event
- VSA, 208 hr/yr
- Gas compressors, assumed to be 1 hr/d

7.1.3 Cost Summary

A summary of the capital and O&M costs for the systems is presented in **Table 10**. Note that this analysis assumes \$20/hr for O&M labor and electrical energy costs at \$0.10/kWh.

Table 10. Capital and O&M Costs.

Process	Capital			O&M		
	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel
Digestion	\$500,000	\$800,000	\$1,400,000	\$30,000	\$30,000	\$30,000
Microturbine	\$420,000	\$520,000	\$800,000	\$20,000	\$20,000	\$20,000
Injection into natural gas pipeline (VSA)	\$310,000	\$400,000	\$550,000	\$40,000	\$60,000	\$100,000
Vehicle Fuel with VSA	\$450,000	\$770,000	\$1,040,000	\$40,000	\$60,000	\$120,000
Vehicle Fuel with water scrubber	\$430,000	\$740,000	\$1,000,000	\$50,000	\$50,000	\$70,000

7.1.4 Revenue and Cost Offsets

The CHP facility will produce electrical power that can be used to reduce facility power costs. The heat from the CHP system is considered to be utilized for digester heating and not to have value beyond the process. Based on the previously estimated power production, the CHP option will offset the following electricity purchases:

- 10,000 personnel base, 290,000 kWh/yr
- 20,000 personnel base, 590,000 kWh/yr
- 40,000 personnel base, 1,170,000 kWh/yr

Based on the methane produced and assuming a 94% recovery of methane in the gas scrubbing technologies and parasitic gas demands for boiler heating, the total methane produced in terms of gigajoules (GJ) is as follows:

- 10,000 personnel base, 2,800 GJ/yr
- 20,000 personnel base, 5,700 GJ/yr
- 40,000 personnel base, 11,400 GJ/yr

In terms of gasoline gallon equivalents (GGEs) the gas estimates are as follows:

- 10,000 personnel base, 25,000 gal/yr
- 20,000 personnel base, 50,000 gal/yr
- 40,000 personnel base, 99,000 gal/yr

The estimated fuel production for USAFA was 6,000–10,000 GGE/yr.

Assuming average electrical purchase costs of $0.10/kWh, minus 1¢/kWh for engine maintenance, using the current Henry Hub natural gas price of $2.65/GJ and current gasoline prices across the United States of $2.319/gal, the following revenue or cost offsets are available to the alternatives.

As power purchase offsets:

- 10,000 personnel base, $30,000/yr
- 20,000 personnel base, $50,000/yr
- 40,000 personnel base, $110,000/yr

As wholesale natural gas:

- 10,000 personnel base, $10,000/yr
- 20,000 personnel base, $20,000/yr
- 40,000 personnel base, $30,000/yr

As gasoline:

- 10,000 personnel base, \$60,000/yr
- 20,000 personnel base, \$120,000/yr
- 40,000 personnel base, \$230,000/yr

7.2 COST DRIVERS

Non-technical cost drivers included installation population, local costs of food waste disposal alternatives (e.g., landfilling or composting), trucking fees associated with food waste transportation, and the cost of gasoline or diesel fuel. Technical cost drivers included the organic loading rate to the digester, gas purification requirements, and the selected gas purification technology. Finally, the ultimate end use of the biogas or biomethane had a large impact on cost effectiveness of the technology. The technology was initially estimated to be cost-effective when the price of gasoline is \$4/gal and the landfill tipping fee is \$100/ton (Evans et al. 2016). As of the date of this report, the price of gasoline is <\$3/gal but has been >\$4/gal in the past. Landfill tipping fees vary widely across the country and can be expected to increase. As described in Section 7.3, the technology was cost-effective under a broader range of scenarios than originally predicted.

7.3 COST ANALYSIS

In Section 7.1, the costs and projected revenues for two different digestion and gas utilization technologies were compared. Based on that evaluation, it appears that scrubbing the biogas to natural gas is not a cost-effective technology. Additionally, the comparison of a high-pressure water scrubber for gas treatment to VSA suggests they have similar costs. This section of the report evaluates the cost effectiveness of the various technologies. Based on Section 7.2, the high pressure water scrubber has capital costs and net revenues as presented in **Table 11**.

Table 11. Capital Costs and Net Revenues for Different Alternatives.

Process	Capital			Net Revenues		
	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel
Digestion and CHP	\$920,000	\$1,320,000	\$2,200,000	(\$20,000)	\$0	\$50,000
Digestion and natural gas production	\$810,000	\$1,200,000	\$1,950,000	(\$60,000)	(\$70,000)	(\$110,000)
Digestion plus VSA for vehicle fuel	\$950,000	\$1,570,000	\$2,440,000	(\$10,000)	\$30,000	\$70,000
Digestion plus high pressure water scrubber for vehicle fuel	\$930,000	\$1,540,000	\$2,400,000	(\$20,000)	\$40,000	\$120,000

Using an analysis period of 20 yr and a discount rate of 1.2% (based on the real interest rate of a 20-yr note), the above costs can be presented in terms of net present cost and as annualized cost as illustrated in **Table 12**.

Table 12. Net Present and Annualized Costs for Different alternatives.

Process	Net Present Cost			Annualized Cost		
	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel	10,000 Base Personnel	20,000 Base Personnel	40,000 Base Personnel
Digestion and CHP	$1,270,000	$1,320,000	$1,320,000	($70,000)	($70,000)	($70,000)
Digestion and injection into natural pipeline	$1,870,000	$2,440,000	$3,900,000	($110,000)	($140,000)	($220,000)
Digestion plus VSA for vehicle fuel	$1,130,000	$1,040,000	$1,200,000	($60,000)	($60,000)	($70,000)
Digestion plus high pressure water scrubber for vehicle fuel	$1,280,000	$830,000	$280,000	($70,000)	($50,000)	($20,000)

Although none of the alternatives show a net revenue over the 20-yr planning period when amortized capital costs are considered, the current food waste handling systems also have costs associated with them. Considering that the estimated tons processed by the bases over the year are 1,200 ton/yr, 2,300 ton/yr, and 4,600 ton/yr for the 10,000, 20,000, and 40,000 personnel base, respectively, the cost of food waste disposal is significant. Based on these yearly estimated food waste production values the net cost for food waste disposal via digestion with CHP for energy recovery is as follows:

- 10,000 personnel base, $58/wet ton
- 20,000 personnel base, $30/wet ton
- 40,000 personnel base, $15/wet ton

Net cost for food waste disposal in an anaerobic digester with biogas captured and scrubbed to natural gas quality for sale to the natural gas utility has the following costs per ton of food waste generated:

- 10,000 personnel base, $92/wet ton
- 20,000 personnel base, $61/wet ton
- 40,000 personnel base, $48/wet ton

For the digestion with methane converted to compressed natural gas for vehicle fuel using SulfaTrap™ and a VSA, the annual food waste disposal cost is as follows:

- 10,000 personnel base, $50/wet ton
- 20,000 personnel base, $26/wet ton
- 40,000 personnel base, $15/wet ton

Using the anaerobic digester for food waste processing and scrubbing the gas with a water scrubber prior to compressing for fueling vehicles, the following net food waste disposal costs result:

- 10,000 personnel base, $58/wet ton
- 20,000 personnel base, $22/wet ton
- 40,000 personnel base, $4/wet ton

In comparison, average landfill costs across the United States are ~$50/wet ton (Clean Energy Projects Inc. 2015). In comparison to composting, institutional onsite composting facilities have a net cost of ~$29/wet ton and commercial composting facilities have a net cost of ~$52/wet ton (Sparks 1998). Thus, even at the smaller 10,000 personnel base, the technology is cost competitive with landfilling and offsite composting (**Figure 23**). For installations serving a population of 20,000, food waste disposal through anaerobic digestion and biogas recovery either as a vehicle fuel or in a CHP facility is cost competitive with institutional onsite composting. At larger bases of around 40,000 personnel, disposal of food waste via anaerobic digestion and biogas purification appears to have economic advantages compared to traditional food waste disposal methods.

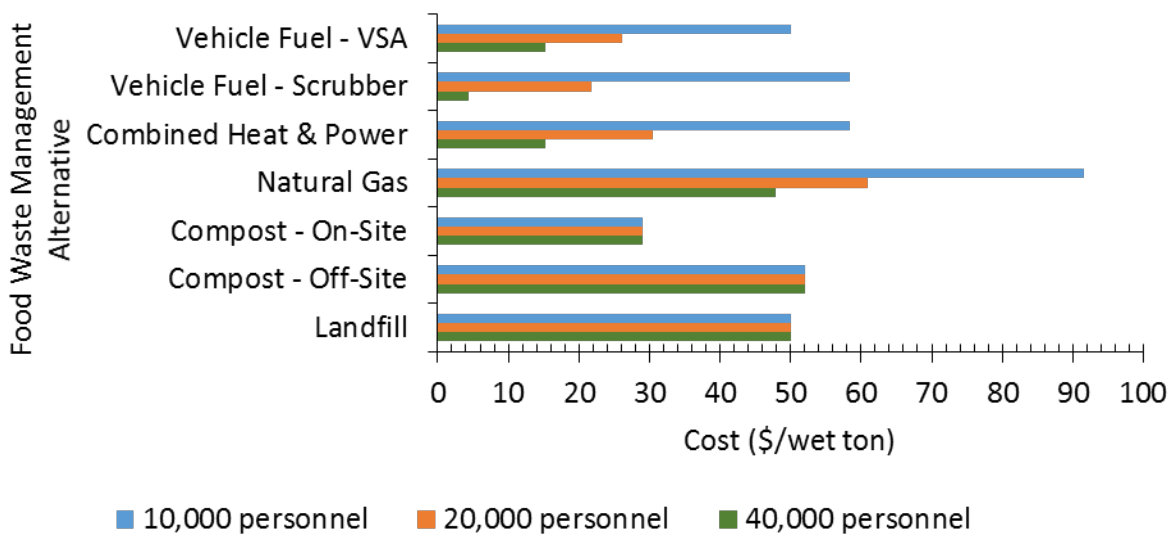

Figure 23. Comparison of Food Waste Management Alternatives.

8.0 IMPLEMENTATION ISSUES

This project has shown that anaerobic digestion of food waste at military bases is technologically feasible and can be cost competitive with alternative methods of food waste management depending on the size of the installation. Often anaerobic digestion systems are custom-designed and built. However, in recent years, a number of companies have emerged that specialize in the manufacture of onsite anaerobic digestion systems. One important consideration for a military installation is the availability of staff to operate and maintain what is essentially a WWTP. Clearly, if the installation already had a WWTP onsite such as USAFA, then the implementation is much easier. Alternatives do exist as described in the Engineering Guidance Report (Vandenburgh and Evans 2016). This document is intended to facilitate technology evaluation, selection, and implementation. The alternatives include transport to a local wastewater reclamation facility that has the capability of accepting food waste and FOG.

This study attempted to cover all the costs associated with food waste digestion, but it is likely some costs may not be included. Investigations may be required to quantify some of the hidden costs: For vehicle fuel options, the cost of converting the vehicles to run on compressed natural gas is not included. An approximate cost to convert a vehicle from gasoline to compressed natural gas is $6,000–$8,000. This is based on the range of costs of newly purchased vehicles with either a gasoline or a compressed natural gas engine. A second cost not incorporated into the analysis is the disposal of the digestate. The expected digestate volume is estimated to be <5% of the estimated wastewater that would be generated by similarly sized plants. As such, it may be possible to route the digestate through the facility sewer system. However, due to the likely strength of the digestate, the local sewer authority may restrict the discharge or impose a fee for disposal. Consultation with the local sewer agency would be required prior to discharging the digestate in the sewer.

This study was conducted at a time when gasoline prices were relatively low. In the recent past, gasoline prices were >$4/gal. At these prices, the value of the technology would be greater. Additionally, the study assumed an aggregate rate of electricity at $0.10/kWh. Electricity prices vary greatly across the country. Further, electricity pricing in some areas and for larger customers can be more complicated. Finally, the treatment system would generate more power than the system uses. As such, the treatment system may require a power purchase agreement as well as additional relays and switches to protect the grid. The electric utility may not provide $0.10/kWh in a power purchase agreement. Another factor affecting technology cost-effectiveness is local landfill tipping fees. Greater landfill tipping fees will result in the technology being more cost effective.

Design of the facilities would need to be in compliance with all building codes and in compliance with the National Fire Protection Association (NFPA) and the National Electrical Code (NEC). There currently is not an NFPA code that pertains to mono-food waste digestion facilities. However, guidance could be provided in NFPA 820 for WWTPs.[1]

[1] http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code&code=820.

The technology would have a net reduction of GHG emissions compared to landfilling and composting (Parry 2014). This technology could be used to help DoD facilities move into compliance with EO 13514, which calls for agencies to set percentage reduction targets for GHG emissions for FY2010. Specifically, the order addresses reducing fossil fuel use in vehicles.

Table 13 presents the design criteria that can be used to size equipment and facilities for an independent food waste handling system. It should be noted that **Table 13** does not include the influent characteristics of the food waste. These characteristics should be assessed based on actual food waste data from the plant. The researchers recognize that the food waste generated at the USAFA and used as the basis for this study may be different than that at other facilities. Further, the processing applied at the USAFA—specifically the grinder and pulper—may not exist at all facilities. As a result, the facility will need to work with potential vendors of food waste pulping and grinding systems. These vendors are likely to process the food waste differently, which may have impacts on the food waste concentration and other characteristics. Additional engineering design guidance is provided in the companion Engineering Guidance Report (Vandenburgh and Evans 2016). Food waste characteristics will affect digester performance, but COD and SELR were determined to be useful parameters for evaluating food waste suitability. In addition, experience with co-digestion of food waste also suggests a minimum COD of 20,000 mg/L with the optimum >50,000 mg/L (Hare 2016). The minimum VS/TS value is 65% with the optimum being >85%. Also, refer to Appendix C in the Final Report (Evans et al. 2016) for information relevant to desired waste stream characteristics.

Table 13. Design Criteria for an Independent Food Waste Handling System.

Parameter	Suggested Design Value	Comments
Methane Production (VS basis)	400 L CH_4/kg VS loaded	Use design value to predict methane production from digester. Use for sizing gas utilization equipment and determining potential revenues and offsets from biogas utilization
Methane Production (COD basis)	250 CH_4/kg COD loaded	Use design value to predict methane production from digester. Use for sizing gas utilization equipment and determining potential revenues and offsets from biogas utilization
Specific COD loading rate (SELR)	0.44 g-COD/g-VSS/d	Use design value for sizing the anaerobic digestion facilities
pH	7.8	Design value for understanding operational pH in digester
TS Reduction	78%	Use design value for projecting solids to be disposed after process
VSS Reduction	92%	Use in combination with SELR to size anaerobic digestion facilities
Biogas CH_4 Content	60%	Use in combination with methane production to determine size of required digester gas piping and other digester gas conveyance system, flares, etc.
Biogas H_2S Content	2,900 mg/m^3	Use to size H_2S) removal systems

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